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Silicon (Si): A Regulator Nutrient for Optimum Growth of Wheat Under Salinity and Drought Stresses- A Review

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Abstract

Abiotic stresses such as salinity and drought stresses are known as the main constraints for optimum growth of plants, especially in arid and semi-arid regions. Therefore, in recent years, agricultural scientists have begun to research about the fertilizers that have a multifaceted use and can be used to maintain the optimum growth and yield of strategic plants under environmental stresses. Since wheat is the most important crop worldwide, stress tolerance plays a crucial role in food security. By different mechanisms, silicon (Si) improves the tolerance of plants to salinity and drought stresses including regulation of plant water relationships, gas exchange, photosynthesis, nutrient balance, reducing oxidative stress, reducing ionic toxicity, osmoregulation and root growth, potassium uptake, and stimulation of plant hormones. In the present work, the effects of Si on wheat tolerance to salinity and drought stresses will be discussed and it will try to explain the involved mechanisms in the regulation of the plant growth and yield by Si. This study also highlights the need for future research on the role of Si in wheat under drought stress and in saline soils.

Keywords Silicon · Drought stress · Salinity stress · Nutrient management · Wheat

Introduction

Nowadays, intensive agriculture has been primarily limited by abiotic and biotic stress throughout the world (Ramegowda et al. 2020; Ranjan et al. 2021; Mousavi et al. 2022). Among abiotic stresses, salinity and drought are two main constraints in arid and semi-arid regions that negatively affect plant growth and yield, especially in wheat (Ding et al. 2020; Saddiq et al. 2019; Basirat et al. 2019). About 30% of the land in the world is affected by drought stress. Daryanto et al. (2016) and Rasool et al. (2013) reported that drought and salinity stress annually decreased plant production by 20% and 1–2%, respectively. Irrigation with saline water, improper drainage principles, and unbalanced use of chemical fertilizers are considered the main reasons for increasing soil salinity (Corwin 2021; Majeed and Muhammad 2019). Other abiotic stresses, including heavy metal contamination, cold, frost, and UV-B light, destructively affect agricultural products, but their adverse effects on plants are less than those of drought and salinity stresses (Aminiyan et al. 2022; Etesami and Jeong 2018).

Optimal plant growth depends on the uptake of a wide range of nutrients, which are divided into three groups: essential, beneficial, and toxic elements. Silicon was previously not considered an essential element for plants because the role of Si in plant metabolism had not yet been determined (Arnon and Stout 1939). However, its classification as a beneficial element has been recognized for more than 50 years (Marschner 2011; Mousavi 2022). The studies have confirmed its beneficial effects on a variety of species growing under a wide range of environmental conditions

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(Mousavi et al. 2018a, 2018b, 2022). This overwhelming evidence, together with studies of Si transporters in plants and the yield benefits of Si fertilization of crops, eventually led the International Plant Nutrition Institute (IPNI) to upgrade Si from complete omission to a listing as a beneficial substance in 2015 (Coskun et al. 2019). The essentiality of Si for plants has been the subject of a long debate dating back to the nineteenth century (Sreenivasan 1934; Katz et al. 2021). Because the growth of some plants depends on Si, the supply of Si leads to optimal growth and yield (Puppe and Sommer 2018; Souri et al. 2021).

Plants absorb Si in the form of silicic acid $[Si(OH_4)]$ through aquaporin channels, and Si uptake can be active or inactive. Most plants have Si carriers that increase Si uptake (Exley et al. 2020). Plants differ significantly in their ability to absorb Si. Depending on the plant species, the concentration of Si in plant tissues ranges between 0.1 and 10% of dry weight (Liang et al. 2007). In Table 1, plants are classified according to Si content in plant tissues. The concentration of Si in monocots (10–15%) is higher than that in dicots (0.5%) or less in the order of grain products > grasses > vegetables > fruits > legumes (Thiagalingam et al. 1977). Generally, plants have different potentials for the uptake and accumulation of Si. Some plants, such as sugarcane, rice, and wheat, can be considered Si accumulator species, in which the rates of Si absorption have been reported 300–700 kg ha^{-1}, 150–300 kg ha^{-1}, and 50–150 kg ha^{-1}, respectively (Bazilevich 1993).

Wheat (*Triticum aestivum* L.) is one of the most important cereals in terms of food security throughout the world, provides 30% of the calories and 60% of the protein consumed in the world (Grote et al. 2021). The World Bank estimates that in 2050, demand for wheat in developing countries will increase by about 60% (Akram et al. 2021). Because of a significant decrease in wheat production caused by different stresses, finding solutions to increase stress tolerance has been the focus of numerous studies over the last few decades. Wheat is a semi-sensitive crop to salinity. The salinity threshold in wheat is 6 dS.m^{-1}, with a 7.1% yield loss, and at 13 dS.m^{-1}, the yield loss is 50% (Asgari et al. 2011; Maas and Hoffman 1977). Depending on its severity and plant variety, drought stress can reduce the yield of wheat from less than 5% to more than 50% (Anwaar et al. 2020). When the soil moisture decreased from 80% of the field capacity to 60% (medium stress), the grain yield and shoot dry matter decreased by 21 and 13%, respectively, and when the moisture decreased to 40% of the field capacity, the grain yield and shoot dry matter decreased by 43 and 30%, respectively (Ma et al. 2014).

Table 1 Plant classification according to the amount of silicon accumulation (Bakhat et al. 2018)

Non-accumulator < 0.5% Si (Frantz et al. 2011)	Intermediate 1.5–0.5% Si (Pennington 1991)	Accumulator > 1.5% Si (Frantz et al. 2011)
Tomato	Soybean	Rice
Petunia	Pumpkins	Wheat
Pansy	Rose	Ferns
Snapdragon	Squash	Spinach
Geranium	New guinea impatiens	Sugarcane
Gerbera	Marigold	Mosses
Grapes	Cucumber	Horsetail (Equisetum)
Begonia	Chrysanthemums	Lentils
Sunflower	Zinnia	Conifers

The studies have shown that the soil and foliar application of Si under drought and salinity conditions not only improves the plant's resistance but also results in significantly increased growth and yield in wheat (Alzahrani et al. 2018; Taha et al. 2021). Some important mechanisms involved in plant resistance to drought and salinity stresses affected by Si nutrition are as follows: enhancing gas exchange, membrane stability, potassium (K) adsorption, improving the activity of antioxidant enzymes, reducing the content of sodium (Na) and malondialdehyde, and reducing electrolyte leakage (Alzahrani et al. 2018; Coskun et al. 2016; Verma et al. 2020). The purpose of this review is to look into various aspects of wheat plant responses to Si nutrition under drought and salinity stress conditions.

The authors made an attempt to analyze the different areas of silicon research published through the Web of Science, Google Scholar, Springer Link, and Wiley Blackwell databases using keywords such as silicon, wheat, drought, salinity, and nutrient management. The results showed that more than 316,000 references on the subject of silicon were published from 2010 to 2021. We finally identified 120 research papers for our review manuscript, covering 30 review papers and 90 research papers. Through these literature reviews, we were able to identify the gap in Si research, which focuses on the effect of Si on improving the growth and yield of wheat under environmental constraints like drought and salinity stresses.

The Sources of Si for Use in Agriculture

The ideal Si fertilizers have a high amount of available Si, the facility of mechanized application, high amounts of calcium (Ca), magnesium (Salim et al. 2013; Cheraghi et al. 2020, 2022), and K, and low concentrations of heavy metals (Bocharnikova and Matichenkov 2014; Salim et al. 2013) (Table 2). Powder silicates are usually uniformly mixed with the soil, while granules are used linearly with NPK fertilizers. Calcium silicate is a by-product obtained by industrial methods and is one of the most popular Si fertilizers. Despite

Table 2 Some of the common silicon fertilizers in agriculture and research

Source	contents	Chemical composition	Features	Method of fertilizer application	Reference
Silicic acid	29% Si	H_4SiO_4	Primarily absorbed form of plants from soil	Seed treatment, fertigation, nutrition solution	Sebastian et al. (2013)
Potassium silicate (Solution)	10% Si 10% K_2O	K_2SiO_3	Water-soluble Si and K	Soil application, Fertigation, Seed treatment, Nutrition solution	do Ministro (2012);Ahmad (2014)
Calcium silicate	20% Si 29% Ca	$CaSiO_3$	High solubility in water; low bulk density	Soil application, fertigation, nutrition solution	Alcarde and Rodella (2003); do Ministro (2012)
Calcium and magnesium silicate	10% Si 1% Mg 7% Ca	$CaSiO_3$/$MgSiO_3$	High solubility in water	Soil application	do Ministro (2012); Castro et al. (2016)
Sodium silicate	23% Si	Na_2SiO_3	Water-soluble; stable in neutral and alkaline solutions	Soil application, fertigation, seed treatment, nutrition solution	Abed-Ashtiani et al. (2012)
Silica gel	46.7% Si 5.8% Soluble Si	Not known (SiO_2.nH)	High specific surface area (around 750–800 $m^2.g^{-1}$)	Soil application, Seed treatment, and foliar spray	Sebastian et al. (2013)
Miscanthus biochar	38.3% Si	SiO_2	Organic resource	Soil application	Houben et al. (2014)
Rich hull ash	> 28.0% Si	SiO_2	Organic resource		
Rice hull fresh	7–9.2% Si			Soil application	Sun and Gong (2001); Kalapathy et al. (2002); do Ministro (2012)
Quartz sand	46% Si		Low solubility		

its high price, potassium silicate, because of its considerable solubility, is used in hydroponic systems and foliar spraying (Rao and Pusarla 2018).

In addition to chemical (mineral) sources, Si can also be supplied from organic sources. Rice husks, rice husk ash, rice straw, and biochar are organic sources of Si (Rizwan et al. 2019; Sahebi et al. 2015). The average Si content in rice straw and husk is between 4.20 and 9.26%, respectively (Rao and Pusarla 2018). Silicon-solubilizing bacteria (SSB), which generally belong to the genus Bacillus, can also be used as biological fertilizers (Rezakhani et al. 2020). These bacteria dissolve silica and make it available to the plant, increasing its resistance to biotic and abiotic stresses. For more comprehensive information on silicon and silicon fertilizers, reviews published by Rao and Pusarla (2018), Savant et al. (1999), and Bocharnikova and Matichenkov (2014) are recommended.

The Role of Si in Wheat Tolerance to Drought and Salinity Stress

Drought Stress

Drought stress is a multidimensional stress that causes changes in the physiological, morphological, biochemical, and molecular traits of wheat (Nezhadahmadi et al. 2013; Belay et al. 2021) that can occur at any stage of plant growth and development (Basirat and Mousavi 2022; Mousavi 2022). Depending on the growth stage, intensity, and duration of the stress, drought stress causes a decrease in RWC, chlorophyll degradation, a decrease in leaves' size, a lower aperture, a decrease in the number of stomata, cell wall thickening, cutinization of the leaf surface, stomatal closure, increased osmolytes, and growth inhibition in wheat, ultimately leading to yield loss and productivity (Sharifi and Mohammadkhani 2016). The effect of drought stress on grain yield and other agronomic components was highly pronounced at the tillering stage (72% reduction), flowering stage (37%), and grain filling (17.1%) as compared to the well-watered treatment (Ashinie and Kindie 2011). Silicon application can increase drought resistance and yield of wheat (Ahmad et al. 2016; Alzahrani et al. 2018; Valizadeh-rad et al. 2022a). Under drought stress, Si increases wheat resistance by increasing leaf membrane stability, relative leaf water content, photosynthesis, osmotic regulation, reducing oxidative stress, modifying gene expression, synthesizing phytohormones, and increasing epicuticular wax production, which is discussed in the following sections (Rafi et al. 2020; Rizwan et al. 2015).

Water Relations and Photosynthesis

Maintaining water relations in a stable and optimal condition is vital for the growth and development of wheat under drought stress (Belay et al. 2021). A reduction or inhibition of photosynthesis is one of the main effects of drought in higher plants (Keyvan 2010). Drought stress in wheat decreases the leaf chlorophyll content, the number and surface size of leaves, and consequently the number of stomata, as a result of which the stomatal conductance decreases and the stomata close (Salehi-Lisar and Bakhshayeshan-Agdam 2016). Carbon dioxide limitations due to prolonged stomatal closure lead to the accumulation of reduced photosynthetic electron transport components. The accumulation of these compounds can reduce molecular oxygen and give rise to the production of reactive oxygen species (ROS) such as superoxide and hydroxyl radicals as well as H_2O_2, thus causing oxidative damage in chloroplasts (Nezhadahmadi et al. 2013; Sehar et al. 2021; Ullah et al. 2021). ROS can damage the photosynthetic apparatus, including thylakoid membranes, photosynthetic pigments, and enzymes (Sehar et al. 2021). Silicon can retain water relationships and increase water use efficiency in wheat by various mechanisms (Xu et al. 2017). Applying Si to wheat plants exposed to drought stress reduces water loss through stomata, increases relative leaf water content, and produces more extensive and thicker leaves, thereby reducing water loss through transpiration (Rafi et al. 2020). Under drought stress, the application of Si leads to an increase in K content in leaves, stems, and grains of wheat, which helps maintain water balance in the plant and increases the plant's resistance to drought stress (Ahmad et al. 2016). Subsequently, K, through controlling the opening and closing of stomata, reduces transpiration and prevents plant water loss (Ahmad et al. 2018).

Drought stress significantly reduces photosynthetic pigments in wheat. The studies show that under drought conditions, Si significantly increases photosynthetic pigments and photosynthesis in wheat (Bukhari et al. 2020), due to increased activity of ribulose bisphosphate carboxylase, glyceraldehyde-3-phosphate dehydrogenase dependent on $NADP^-$, photosynthetic enzymes, and chlorophyll content (Gong et al. 2005). Silicon deposition in plant tissues increases the plant's tolerance to water-deficit stress by reducing transpiration and keeping the leaf blade upright (Salman et al. 2012). The previous studies showed that foliar application of Si increased photosynthetic pigments (chlorophyll a, b, total chlorophyll, and carotenoids) in four wheat cultivars under drought and non-stress conditions, and the rate of increase was higher under stress conditions (Maghsoudi et al. 2015). Furthermore, the positive effect of Si on photosynthesis through different physiological and biochemical mechanisms has been reported in previous studies (Gong and Chen 2012; Maghsoudi et al. 2018).

Relative Water Content (RWC)

When wheat is exposed to drought stress, the water content and water potential of the leaves are significantly reduced (Farooq et al. 2009). Under these conditions, Si can improve the water status of the plant (Othmani et al. 2021). In another study, it was reported that foliar application of Si increased the relative leaf water content in four wheat cultivars (Sirvan and.Chamran, as relatively drought-tolerant, and Shiraz and Marvdasht, as drought sensitive) under drought stress (Maghsoudi et al. 2015). Stomatal conductivity and the rate of transpiration largely determine the relative water content of the leaves, and an accumulation of Si in the epidermal tissues as a thin membrane of siliceous cellulose can protect plants from water loss through the cuticular perspiration by forming a double layer of silica cuticle in the epidermis of the leaf tissue (Farooq et al. 2009; Mvondo-She and Marais 2019).

Silicon reduces stomatal and cuticle transpiration (Vandegeer et al. 2021). Accumulation of monosilicic acid or polymerization of silicic acid in the cell wall of the epidermis may form hydrogen bonds between water and hydrated silica (SiO_2–nH_2O); in this way, water molecules are not able to transpire quickly from the leaf surface (Liang et al. 2008; Vandegeer et al. 2021). When wheat and other crops become dehydrated, their first response is to close the pores to prevent water loss through transpiration (Chaves et al. 2002). Closure of the pores is one of the main factors in reducing photosynthesis because it reduces the amount of CO_2 entering the leaf (Blanke and Cooke 2004). Silicon precipitates around the protective cells of the stomata and in the cell wall of these cells and prevents the pores from closing completely, thus reducing perspiration from the stomata and maintaining photosynthesis (Maghsoudi et al. 2016; Vandegeer et al. 2021).

Nutrient Uptake

Silicon plays a vital role in the balanced uptake, distribution, and transport of nutrients in plants under drought stress. Basirat and Mousavi (2022) reported that under water stress, Si application increases K, Ca, and Mg uptake. Numerous studies have only stated that under drought stress, the application of Si leads to an increase in Mg uptake in wheat, but they have not investigated the mechanism of its effect (Bukhari et al. 2015; Basirat and Mousavi (2022). Greger et al. (2018) reported that the addition of Si increased Mg uptake and accumulation in the shoots of several species grown in solution culture with optimal nutrient supply. To date, the effect of Si on the expression of Mg transporters has not been demonstrated (Pavlovic et al. 2021). There are only two studies that have investigated the effect of Si on Mg-deficient plants. Buchelt et al. (2020) reported Si-mediated alleviation of Mg stress in forage crops but attributed it to increased Mg use efficiency rather than increased Mg uptake. In another study, Hosseini et al. (2019) showed that the Si application had no influence on the uptake or translocation of Mg. Ahmad et al. (2016) reported that Si has a significant effect on increasing K concentrations in shoots and grains of wheat under drought. Increasing Ca and K uptake can be attributed to the effect of Si on reducing the permeability of the plasma membrane and increasing plasma membrane H^+-ATP activity (Liang et al. 2006). K and Ca play a vital role in expressing genes that are activated in response to osmotic stress (Al-Bahrany and Al-Khayri 2012). Some of the mechanisms by which silicon alleviates nutrient deficiency, toxic-induced drought, and salinity stress are shown in Fig. 1.

Growth and Yield

The effects of Si on plant growth under stressed or non-stressed conditions depend on plant species and the dose of Si application (Basirat and Mousavi 2022; Rezakhani et al. 2020). Silicon increases photosynthesis by increasing the activity of the Rubisco enzyme and the amount of chlorophyll in leaves (Saud et al. 2016). They increase the content of photosynthetic pigments (chlorophyll a, b, and carotenoid) in the plant, affect cell division and growth, improve morphological and physiological properties, and finally increase vegetative growth by increasing the number of leaves (Gunes et al. 2007). Increasing the leaf number results in more leaf surface and a light interception to produce dry matter more quickly (Sivanesan et al. 2010). Overall, the application of Si increases photosynthesis by increasing the amount of chlorophyll, Rubisco enzyme activity, and the number and area of leaves as a result, the amount of carbohydrates and photosynthetic reserves increases (Savvas and Ntatsi 2015). Silicon can also increase the synthesis of soluble proteins (Bharwana et al. 2013; Pei et al. 2010; Xu et al. 2017). The effect of Si on improving shoot growth under water deficit ultimately increases the grain yield (Walsh et al. 2018). Soratto et al. (2012) showed that Si fertilizers increased the yield of wheat and oats by 27 and 34%, respectively, compared to non-Si applications.

Behboudi et al. (2018) found that the foliar and soil application of Si nanoparticles under drought stress increased wheat yield by 25 and 18%, respectively. Silicon fertilization

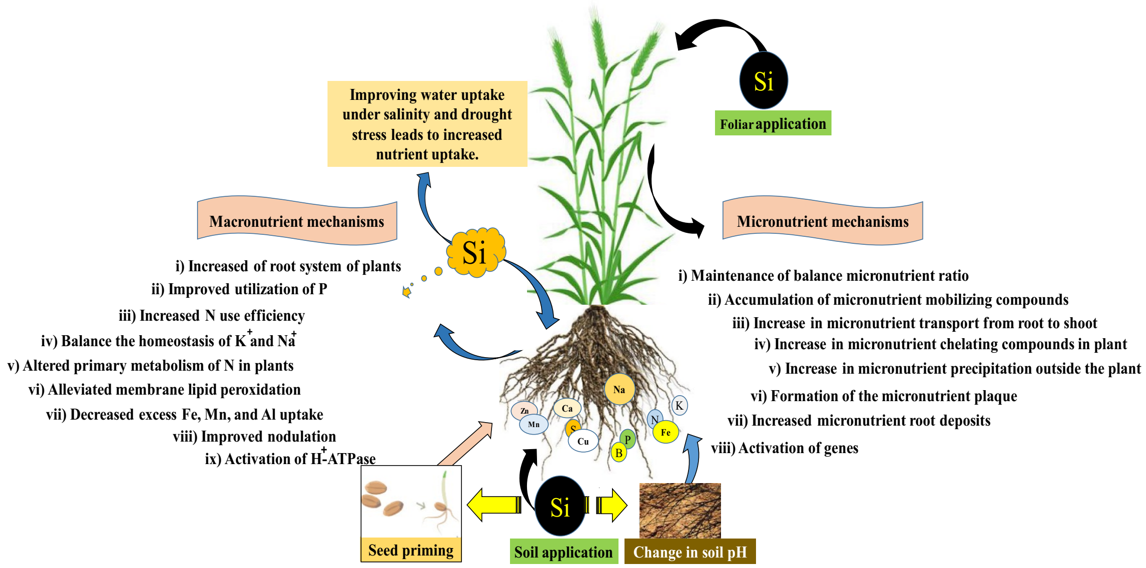

Fig. 1 A summary of mechanisms by which Si alleviates nutrient deficiency affected by drought and salinity stresses in wheat. For details, see the text (Sects. 3–1-3 and 3–2-6) and also these references (Liang et al. 2006; Kaya et al. 2006; Eneji et al. 2008; Ali et al. 2009; Frantz et al. 2011; Salim et al. 2013; Gurmani et al. 2013; Chen et al. 2014; Rizwan et al. 2015; Ahmad et al. 2016; Daoud et al. 2018; Zhang et al. 2018; Huang and Ma 2020; Vandegeer et al. 2021; Akhter et al. 2021; Basirat and Mousavi 2022; Mousavi 2022; Valizadeh-rad et al. 2022b)

also increased fertile tillers/m^2, plant height, spike, and spike length by 18%, 5%, 6%, and 9%, respectively, compared with the treatments without Si (Ahmad et al. 2016).

Effect of Si on Reducing Oxidative Stress

The antioxidant defense system in the wheat and other plants' cells includes both enzymatic [such as superoxide dismutase (SOD), catalase (CAT), POD peroxidase (POD), ascorbate peroxidase (APX), glutathione reductase (GR), etc.] and nonenzymatic constituents [such as cysteine (Cys), reduced glutathione (GSH), ascorbic acid (Asc), etc.] (Gong et al. 2005). Under drought stress, high activities of antioxidant enzymes and high contents of nonenzymatic constituents are important for wheat to tolerate stress. Therefore, the influence of Si on each of these compounds can lead to the positive response of the wheat to oxidative stress induced by drought (Table 3). Silicon can reduce oxidative damage to wheat by enhancing the activities of superoxide dismutase, glutathione reductase, and catalase and reducing the amount of hydrogen peroxide and phospholipase activity (Mushtaq et al. 2020). Application of sodium metasilicate under drought stress increased the activity of antioxidant enzymes such as APX, POD, and CAT; the foliar application had the highest efficiency on wheat resistance to drought stress compared to fertigation and seed priming (Bukhari et al. 2015).

In the plant cell, the acid phospholipase (AP) is a kind of hydrolysis enzyme of phospholipids, and its activity can be taken as an indicator of de-esterification of phospholipids (Cuyas et al. 2022). Under drought stress, the application of Si prevents the increase of AP activity and alleviates the de-esterification of phospholipids in wheat plants (Gong et al. 2008). Silicon enhances plasma membrane H$^+$-ATPase activity by reducing oxidative damage to proteins, as demonstrated in drought-tolerant wheat (Gong et al. 2005, 2008; Valizadeh-rad et al. 2022a). The amount of nonenzymatic antioxidants is also increased by using Si (Gunes et al. 2007). One of the several non-protein thiols is glutathione, which acts primarily as an antioxidant in plant cells. Valizadeh-rad et al. (2022b) observed that the addition of Si increased glutathione reductase activity in wheat under water-deficit stress. Also, previous studies showed that with increasing K in plants, the activity of NADPH oxidases (nicotinamide adenine dinucleotide phosphate oxidase) decreased, which in turn led to a reduction in the production of reactive oxygen species, indicating that plant K protects from drought stress (Cakmak 2005). Under drought, the application of Si increases K concentration in wheat plants (Bukhari et al. 2015; Gharineh and Karmollachaab 2013).

Osmotic Adjustment

Drought stress increases osmotic stress in plants, and osmotic regulation is an essential mechanism for tolerating drought stress. The previous studies showed that the use of Si under drought stress increased proline levels in wheat (Ahmad et al. 2016; Maghsoudi et al. 2018). Proline is one of the crucial osmolytes that help cells regulate osmosis, and its accumulation in response to osmotic stress has been widely reported (Koenigshofer and Loeppert 2019; Siddique et al. 2018). Zhang et al. (2017) observed that Si increased the concentration of proline, sugars, and soluble proteins in plants under drought and salinity stresses. Si can also improve water uptake by the roots through the accumulation of amino acids and soluble sugars when plants are prone to water deficiency (Sonobe et al. 2010).

Effect of Si on Plant Hormones

When wheat plants are subjected to drought stress, they use many physiological, morphological, and biochemical mechanisms to resist the drought. These processes are controlled by numerous phytohormones [such as abscisic acid (ABA), auxin, gibberellic acid, cytokinins (CKs), brassinosteroids, jasmonic acid (JA), salicylic acid (SA), ethylene (ET), and strigolactone], which are the basic mediators to tolerate or avoid the negative effects of water deficit (Ullah et al. 2018; Salvi et al. 2021). These phytohormones perform as chemical messengers in response to drought and abiotic stresses. After stress signal perception, phytohormones are released, which activate various plant physiological and developmental processes including stomatal closure, root growth stimulation, and the accumulation of osmolytes to avoid drought conditions (Daszkowska-Golec and Szarejko 2013).

Under drought stress, the application of Si increases the synthesis of some phytohormones such as ABA and JA in wheat plants (Dolatabadian et al. 2009; Xu et al. 2017). Abscisic acid reduces the adverse effects of oxidative stress. Also, by regulating the entry of K into the stomatal guard cells and regulating the opening and closing of the pores, abscisic acid regulates the conduction of the pores and ensures that the plants do not lose more than a certain amount of water under stress (Kim et al. 2014). Xie et al. (2003) stated that under drought stress, indole acetic acid in wheat decreases. Also, they reported that the biosynthesis of indole acetic acid was reduced, which indicates that auxin biosynthesis may be suppressed by drought stress (Du et al. 2013). Xu et al. (2017) showed that Si application reduces the synthesis of jasmonic acid and indole acetic acid and increases the synthesis of abscisic acid in wheat plants. This regulation of phytohormones is associated with improved physiological factors and increased resistance to drought stress by increasing the activity of antioxidant enzymes.

Table 3 The beneficial effect of silicon in reducing the negative effects of drought stress on various parameters of wheat

Parameters	Type of fertilizer	Application details	Observed results	Growth medium	Reference
Growth parameters	Sodium silicate	Mix fertilizer with potting soil (7.14 mmol kg soil^{-1})	Increase of leaf area, dry matter, and plant height	Potted cultivation in greenhouses	Gong et al. (2003)
	Potassium silicate (K_2Sio_3)	Mix fertilizer with soil (50 and 150 mg kg^{-1})	Increase dry weight and shoot height and increase spike weight	Cultivated in 4.5 kg of potting soil	Gong et al. (2008)
	Commercial fertilizer with 8% silicic acid	Foliar spraying (2 l h^{-1})	Increasing the number of spikes and grain yield (26.9 and 34%), increasing dry matter production in wheat and barley	Cultivation in the farm	Soratto et al. (2012)
	Sodium silicate	treatment of seeds in a solution with 20, 40, and 60 mM Si for 8 h	Increase seed germination, germination energy, germination index, and germination rate	Cultivation in a 12 cm petri dish	Hameed et al. (2013)
	Sodium silicate	Application with nutrient solution (150 ppm)	Increase the fresh and dry weight of shoot and increase the weight of root-to-shoot ratio	Greenhouse culture in nutrient solution	Ali et al. (2013)
	Potassium metasilicate	Use as irrigation fertilizer (12 kg h^{-1})	Increase in fresh and dry shoot weight, grain yield, spike length and number of spikes (increase in harvest index)	Cultivation in the farm	Ahmad et al. (2016)
	Acid silicic (29.16% Si) Sodium silicate (22.95% Si) Silica gel (45.16% Si)	Treatment of seeds with Si (seed priming) (1, 0.5, and 1.5%)	Increased grain yield, biological yield, spike length, and 100-grain weight (by increasing Si concentration from 0.5 to 1.5)	Cultivation in 10 kg of potting soil in the greenhouse	Ahmed et al. (2016)
	–	Seed priming (3 mM), Fertilization (1 mM), and foliar application (4 mM)	Improving grain yield and yield components in tillering and pollination stages under non-stressed and drought stress conditions	Potted cultivation in 7 kg of soil in the greenhouse	Bukhari et al. (2020)
	Si nanoparticle	25, 50, and 100 mg kg^{-1}	Increase in dry weight of shoots and roots, plant height and spike length, and dry weight of seeds	Cultivation in potting soil in open space	Khan et al. (2020)
	Sodium silicate (Na_2SiO_3.H_2O)	Application with nutrient solution in hydroponics (150 mg Si l^{-1})	Increase in the shoot (51.31%) and root (54.62%) as compared to the control	Hydroponic culture in nutrient solution	Othmani et al. (2021)
	Sodium silicate	Seed priming)20, 40 and, 60 mM(	Increased shoot biomass yield and 1000-seed weight	Potted cultivation in a mixture of soil, sand, and sludge	Hameed et al. (2021)
	Sodium metasilicate (Na_2SiO_3.$2H_2$)	Irrigation fertilizer (100 mL 1.5 mM, twice weekly)	Lack of observation of the beneficial effect of Si in improving the growth of wheat under drought stress and the need for further research	Greenhouse cultivation in compost medium	Thorne et al. (2021)

Table 3 (continued)

Parameters	Type of fertilizer	Application details	Observed results	Growth medium	Reference
Uptake and accumulation of elements in the plant	Sodium silicate	Application with nutrient solution (1 mM)	Increase concentration of Si in the plant	Hydroponic culture in plastic pots containing nutrient solution	Pei et al. (2010)
	A commercial fertilizer with 8% silicic acid	Foliar spraying)2 l h^{-1}(	Increase in concentrations of Si, N, P, and K (in barley) and increase in Si and potassium concentration (in wheat)	Cultivation in the farm	Soratto et al. (2012)
	Sodium metasilicate	Seed priming (2 mM) Fertigation (0.85g l^{-1}) Foliar spray (1 mM solution pot^{-1})	Increase absorption of K and Si	Potted cultivation in 7 kg of soil in pots	Bukhari et al. (2015)
	Sodium metasilicate	Application with nutrient solution (1 mM)	Increase the amount of Si and Mn uptake and decrease the amount of calcium and potassium	Hydroponic culture in nutrient solution in the greenhouse	Xu et al. (2017)

Table 3 (continued)

Parameters	Type of fertilizer	Application details	Observed results	Growth medium	Reference
Activity of antioxidant enzymes and reactive oxygen species	Sodium silicate	Mix with potting soil (2 mmol kg^{-1} soil)	Increased activity of superoxide dismutase, catalase, ascorbate peroxidase, and peroxidase	Cultivation in potting soil in the greenhouse	Gong et al. (2003)
	Sodium silicate	Mixed with potting soil (2.11 mmol kg^{-1} soil)	Increased activity of glutathione reductase catalase, superoxide dismutase and decreased hydrogen peroxide content and phospholipase acid activity	Planted in 16.95 kg of soil in pots	Gong et al. (2005)
	Sodium silicate	Comes with nutrient solution (1 mM)	Reduces the accumulation of malondialdehyde and H_2O_2 in leaves and increases electrolyte leakage	Hydroponic culture in plastic pots containing nutrient solution	Pei et al. (2010)
	Sodium silicate	Mix fertilizer with soil (2 mM kg^{-1} soil)	Increased activity of catalase, superoxide dismutase, ascorbate peroxidase and peroxidase (it was more robust in the tillering stage)	Cultivation in the soil in pots	Ahmad and Haddad (2011)
	Potassium silicate	Application of 1 mM Si	Increase superoxide dismutase activity and reduce electrolyte leakage	–	Gharineh and Karmollachaab (2013)
	Sodium metasilicate	Seed priming (2 mM) Fertigation (0.85g l^{-1}) Foliar spray (1 mM solution pot^{-1})	Increased ascorbate peroxidase, peroxidase, and catalase activity during tillering and flowering	Planted in 7 kg of soil in pots	Bukhari et al. (2015)
	Sodium metasilicate	Foliar spraying (6 mM)	Decreased electrolyte deposition	Cultivation in the field	Maghsoudi et al. (2016)
	Sodium metasilicate	Application with food solution (1 mM)	Reduction of malondialdehyde, H_2O_2 content, reduction of electrolyte leakage, and increase of catalase activity	Hydroponic culture in nutrient solution in the greenhouse	Xu et al. (2017)
	Si nanoparticle	25, 50, and 100 mg kg^{-1}	Increases the activity of antioxidant enzymes and reduces the content of malondialdehyde, H_2O_2, and electrolyte leakage	Cultivation in potting soil in open space	Khan et al. (2020)
	Sodium silicate	Seed priming 20, 40, and 60 mM	Increased the activity of antioxidant enzymes (SOD, CAT, POX), reduction of malondialdehyde	Potted cultivation in a mixture of soil, sand, and sludge	Hameed et al. (2021)

Table 3 (continued)

Parameters	Type of fertilizer	Application details	Observed results	Growth medium	Reference
Gas exchange and photosynthesis	Sodium silicate	Application in potting soil (2.11 mmol kg^{-1} soil)	Increased chlorophyll a, b, total chlorophyll, and (increased carotenoids but not significant)	Planted in 16.95 kg of soil in pots	Gong et al. (2005)
	Sodium silicate	Mix fertilizer with soil (2 mM kg^{-1} soil)	Increase RWC% and chlorophyll a, b, and total chlorophyll content	Cultivation in the soil in pots	Ahmad and Haddad (2011)
	–	Si applied in soil under field conditions	Increased leaf stomatal conductance, intercellular CO_2 content, and ultimately increased net leaf photosynthesis	Cultivation in the farm	Gong and Chen (2012)
	Sodium silicate	Foliar application (6 mM)	Increasing the concentration of photosynthetic pigments and amount of chlorophyll a and b	Cultivation in potting soil in the greenhouse	Maghsoudi et al. (2015)
	Sodium silicate	Application with a nutrient solution (150 ppm)	Improve water potential and increase chlorophyll content	Greenhouse cultivation in nutrient solution	Ali et al. (2013)
	Sodium silicate	Foliar spraying (6 mM)	Increase in chlorophyll stability index (CSI), increase in photosynthetic pigments (chlorophyll a, b, and total chlorophyll)	Cultivation in the field	Maghsoudi et al. (2016)
	–	Seed priming (3 mM), Fertilization (1 mM), and foliar application (4 mM)	Improving the status of photosynthetic pigments, chlorophyll, and gas exchange during tillering and pollination under normal and stressful conditions	Potted cultivation in 7 kg of soil in the greenhouse	Bukhari et al. (2020)
	Sodium silicate	Application with nutrient solution in hydroponics (150 mg Si l^{-1})	Improve of chlorophyll content (31.08%), shoot (51.31%) and root length (54.62%), as compared to the control	Hydroponic culture in nutrient solution	Othmani et al. (2021)

Table 3 (continued)

Parameters	Type of fertilizer	Application details	Observed results	Growth medium	Reference
Water relations	Sodium silicate	Application in potting soil (2.11 mmol kg^{-1} soil)	Increasing the water content of lipids with unsaturated fatty acids	Planted in 16.95 kg of soil in pots	Gong et al. (2005)
	Sodium silicate	Seed priming (2 mM), Fertigation (0.85g l^{-1}), Foliar spray (1 mM solution pot^{-1})	Increase in water potential, turgor potential, osmotic potential, and relative leaf water content (in tillering and flowering stages)	Planted in 7 kg of soil in pots	Bukhari et al. (2015)
	Acid silicic (29.16% Si) Sodium silicate (22.95% Si) Silica gel (45.16% Si)	treatment of seeds with Si (1, 0.5, and 1.5%)	Increase in relative water content, membrane stability index, and epicuticle wax content in leaves (by increasing Si concentration from 0.5 to 1.5)	Cultivation in 10 kg of potting soil in the greenhouse	Ahmad et al. (2016)
	Sodium silicate	Foliar spraying (6 mM)	Reduce transpiration rate and stomatal conduction	Cultivation in the field	(Maghsoudi et al. (2016)
	Sodium silicate	Application with nutrient solution (1 mM)	Increase in relative leaf water content (RWC%)	Hydroponic culture in nutrient solution in the greenhouse	Xu et al. (2017)
	sodium silicate	Application with a nutrient solution in hydroponics (150 mg Si l^{-1})	Increase in relative water content 21.81% compared to the control treatment	Hydroponic culture in nutrient solution	Othmani et al. (2021)

Table 3 (continued)

Parameters	Type of fertilizer	Application details	Observed results	Growth medium	Reference
Osmolites osmoprotectants	Sodium silicate	Application in potting soil (2 mmol kg^{-1} soil)	Increases the accumulation of proline and soluble proteins and glycine betaine	Cultivation in potting soil in the greenhouse	Gong et al. (2003)
	Sodium silicate	Application in potting soil (2.11 mmol kg^{-1} soil)	Increases the amount of soluble proteins, and the total amount of thiols	Planted in 16.95 kg of soil in pots	Gong et al. (2005)
	Sodium silicate	Application with nutrient solution (1 mM)	Increase in soluble sugars, proline, and glutathione reductase in leaves	Hydroponic culture in plastic pots containing nutrient solution	Pei et al. (2010)
	Acid silicic (29.16% Si) Sodium silicate (22.95% Si) Silica gel (45.16% Si)	Impregnation of seeds with Si (1, 0.5 and 1.5%)	Increase in proline content in leaves (by increasing Si concentration from 0.5 to 1.5)	Cultivation in 10 kg of potting soil in the greenhouse	Ahmad et al. (2016)
	Sodium silicate	Application with nutrient solution (1 mM)	Increase in soluble sugars and ascorbic acid and modulation of endogenous levels of indole acetic acid, gibberellic acid, and abscisic acid	Hydroponic culture in nutrient solution in the greenhouse	Xu et al. (2017)
	Sodium silicate	Seed priming 20, 40, and 60 mM	Increase in total phenolics and proteins, increase in glycine betaine and decrease in proline, increase in cell membrane stability	Potted cultivation in a mixture of soil, sand, and sludge	Hameed et al. (2021)

Table 3 shows the beneficial effects of silicon on reducing the negative effects of drought stress on wheat.

Salinity Stress

Salinity reduces germination, the number of tillers, the size and number of leaves of wheat plants (Grieve et al. 2001), the shelf life of tillers and florets in the spike (Ranjbar 2010), and the number and size of grains with premature aging of the wheat plant (Nadeem et al. 2020). It was reported that salinity stress, depending on the level of salinity, can reduce the yield of wheat plants by 18–80% (Kale Celik 2022). A summary of the adverse effects of salinity on wheat was reported by Sabagh et al. (2021). However, the use of Si can increase salinity tolerance in many critical agricultural products, including wheat (Tibbitts 2018), barley (Akhter et al. 2021), rice (Kim et al. 2014), corn (Ali et al. 2021), tomatoes (Korkmaz et al. 2018), and other agricultural products.

Photosynthesis, Growth, and Yield of Wheat

The cessation or decrease in plant growth caused by salinity is mainly due to the suppression of the photosynthetic system and the decrease in the content of photosynthetic pigments. Under salinity, Si supply can increase leaf chlorophyll a and b and photosynthesis at all stages of growth (Daoud et al. 2018). Jasim and Abood (2018) reported that foliar application of Si significantly increased plant height, leaf area, spike length, and chlorophyll content in six wheat cultivars under saline conditions. In addition, Si-induced reduction of oxidative stress caused by reactive oxygen species leads to a significant increase in chlorophyll a compared to chlorophyll b, leading to an increase in photosynthesis and plant growth (Soratto et al. 2012). Plant growth and metabolic processes are suppressed in salinity due to the overproduction of reactive oxygen species with disrupted plasma membranes and ion imbalance (Liu et al. 2019). In contrast, Si supply reduces the destructive effect of ROS by increasing the activity of antioxidant enzymes such as catalase and superoxide dismutase and thus improving plant growth. For instance, Tahir et al. (2011) applied three Si contents (0, 75, and 150 μg g^{-1} Si using potassium silicate) to both salt-sensitive and salt-resistant wheat varieties at two levels of salinity (0 and 60 mM NaCl). The results showed that at 60 mM NaCl with 150 μg Si g^{-1}, the reduction of grain yield changed from 62 to 33% for the sensitive varieties and from 44 to 20% for the resistant varieties. Also, Ahmad (2014) reported that the application of 2 and 4 mol Si l^{-1} at 100 mol NaCl l^{-1} increased wheat grain yield by 13.8 and 24.2%, respectively, compared to the non-Si application.

Root System

One of the adverse effects of salinity stress in plants is the unbalanced growth of the root system relative to the shoot (Acosta-Motos et al. 2017). Under salinity and drought stresses, the plant faces a water shortage and would spend more energy to increase the volume and surface of the roots, which leads to a sharp decrease in shoot growth and an increase in the root-to-shoot ratio. Studies have found that silica supply improves root growth parameters in wheat under salinity and drought stresses (Daoud et al. 2018; Hameed et al. 2013). Silicon-reinforced root growth can be attributed to the stretching of the cell wall in the area of the root extension (Hattori et al. 2003). Jasim and Abood (2018) reported that Si increased root dry weight in six wheat genotypes, likely by increasing root thickness. Silicon may also increase photosynthesis and accelerate the proliferation of top root cells (Hattori et al. 2003). Some studies showed that Si increases the absorption of water and nutrients by plants by improving the hydraulic conductivity of the roots (Shi et al. 2016), thus increasing the efficiency and activity of the roots (Chen et al. 2011).

Reduction of Sodium (Na) Toxicity

Under salinity, there is competition between Na and K ions which reduces the ratio of K to Na in plants (Zhang et al. 2018). In the presence of Si, a polymer gel is produced in the endoderm and exoderm of the roots of the wheat and rice plants, which reduces the apoplastic transfer of Na ions from the roots to the shoots (Gong et al. 2003; Yeo et al. 1999). Plants take up Si in the form of silicic acid, which is transported to the shoot, and after the loss of water, it is polymerized as silica gel on the surface of leaves and stems (Ma et al. 2001). Also, when the concentration of Si increases in the root, excessive Na is bound in hydrophilic, salicious gel, so both Si and Na are unable to be released in the xylem for upward translocation (Ahmad et al. 1992). Yeo et al. (1999) stated that the deposition of silica in the endodermis and rhizodermis and the polymerization of silicate via colloidal silica to silica gel throughout the root apoplast are possible mechanisms by which Si could physically block the transpirational bypass flow across the roots. Silica gel is formed by acidifying aqueous silicic acid solutions, a process that may be aided by the activity of the root P-ATPase. This could account for the reduction in Na uptake caused by Si that is not accounted for by the effects on transpiration.

Ali et al. (2012) found that saline-tolerant wheat genotypes (SARC-5) showed better performance in response to Si compared to susceptible genotypes (Auqab-200). Under salinity, Si leads to the binding of Na to the cell wall of wheat leaf, which reduces the concentration of free Na in

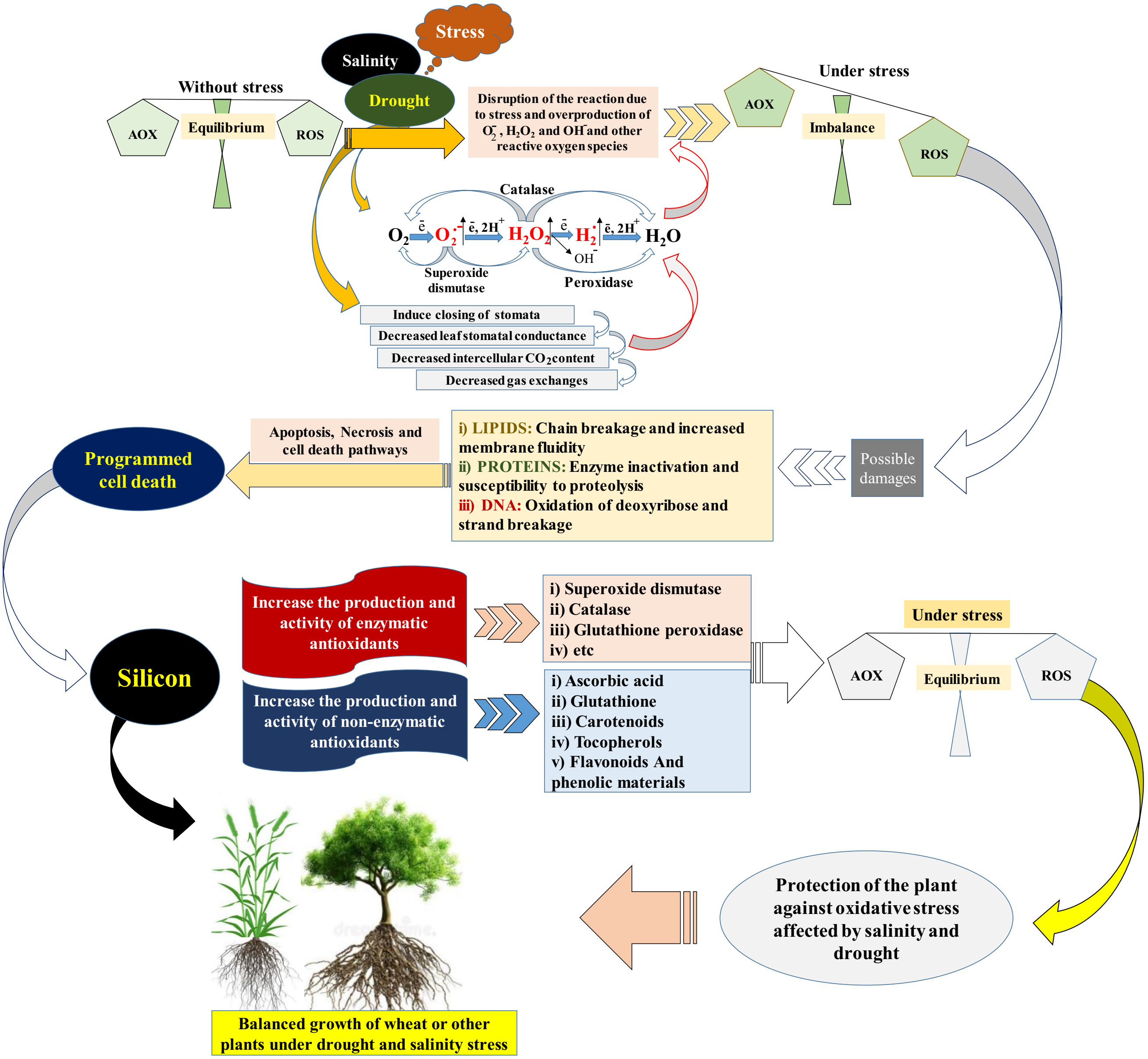

Fig. 2 The involved mechanisms by which Si alleviate oxidative damage affected by drought and salinity stresses in wheat. For details, see the text (Sects. 3–1-5 and 3–2-4) and also these references (Gong et al. 2003, 2005; Gunes et al. 2007; Li et al. 2007; Gong et al. 2008; Ahmad and Haddad 2011; Bharwana et al. 2013; Kim et al. 2014; Ma et al. 2016; Zhang et al. 2017; Taffouo et al. 2017; Ali et al. 2019; Shams et al. 2019; Mushtaq et al. 2020; Verma et al. 2020; Sabagh et al. 2021; Taha et al. 2021)

leaf sap compared to the control treatment (Saqib et al. 2008). Hajiboland et al. (2017) reported that Si decreases the concentration of Na in cell sap and increases its attachment to leaf cell walls, indicating Si detoxification of Na (Ahmad et al. 1992). Silicon can also reduce the transfer of Na to the shoot by forming a Si–Na complex in the root. Silicon application also causes Na accumulation in the roots of the wheat plants and, to a much lesser extent, in the shoots than in the non-Si control (Tuna et al. 2008). Although Si supply reduces the absorption and transportation of Na and maintains a balanced ratio of Na to K in the wheat plant under salinity stress, little is known about whether Si leads to a uniform distribution of Na in the plant or the excretion of Na through exudates and secretions from the roots. There is surprisingly little historical evidence that Si can form a complex with Na. Further studies are also required to provide an optimal level of Si under stress conditions for the wheat plant.

Effect of Si on Salinity-Induced Oxidative Stress

Like drought stress, salinity can disrupt the growth and yield of wheat and other crops by overproducing reactive oxygen species (ROS) (Fig. 2). Application of Si in nutrient solutions increased the activity and production of antioxidant enzymes such as superoxide dismutase and catalase, thus reducing oxidative damage due to salinity stress (Ali et al. 2019). Daoud et al. (2018) applied different amounts of Si to wheat plants under salinity stress and found that Si significantly increased the superoxide dismutase and catalase activity in the leaves of the plants in the start-up stage in relation to a significant reduction in the H_2O_2 content.

Osmotic Adjustment

Salinity stress causes a reduction of leaf water content (RWC), which appears in wheat after a few days of exposure to salinity (Saddiq et al. 2019). The reduction in plant growth under salinity is mainly due to low osmotic potential (Hmidi et al. 2018). Silicon can reduce osmotic stress to some extent by increasing the accumulation of Na in the roots of wheat and preventing its transfer to the leaves, whereas no such effect is observed in plants grown under non-stress conditions (Tuna et al. 2008). Similar results have been reported for sorghum, tomato, and Portulaca oleracea (Kafi and Rahimi 2011; Liu et al. 2015). These studies confirm that Si increases plant tolerance to salinity stress by reducing osmotic pressure.

Most plants under salinity stress accumulate some osmolytes in their tissues in addition to antioxidants. These compounds mainly include proline, glycine betaine (GB), carbohydrates, and polyols (Chen and Jiang 2010; Singh et al. 2015). Studies have shown that treating wheat with Si under salinity stress increases soluble sugars, proteins, and free amino acids, especially proline (Alzahrani et al. 2018; Chen and Jiang 2010). Proline is a non-toxic and protective osmolyte produced under osmotic stress and is often involved in osmotic protection (Szabados and Savouré 2010). Hajiboland et al. (2017) observed that under salinity stress, the proline concentration significantly increased in the leaves of Si-treated wheat. It has also been reported that under salinity stress, proline concentrations decreased with the application of Si in sorghum (Yin et al. 2013), wheat (Tuna et al. 2008), and barley (Gunes et al. 2007). Therefore, there are conflicting reports regarding proline accumulation and the effect of Si on proline content under salinity stress conditions that need further investigation. Saleh et al. (2017) reported that the application of Si (higher than 50 mg kg^{-1} soil) significantly led to an increase in Glycine betaine (GB) concentration in wheat grown under salinity stress. GB accumulation in salt-stressed plants lowers leaf water potential, resulting in improved water uptake by the cells (Ahmad and Haddad 2011). It has also been found that foliar application of nano-silicon fertilizer leads to an increase in the concentration of GB, water-soluble carbohydrates, and free amino acids in wheat plants grown under drought stress (Hajihashemi and Kazemi 2022). The observed increase in the free amino acids in the nano-silicon application can be attributed to their antioxidant power to scavenge free radicals, and osmotic adjustment potential to maintain the cell's osmotic pressure higher than the outer medium to induce water absorbance under stress conditions (Abdel-Haliem et al. 2017; Hajihashemi and Kazemi 2022). Some of the beneficial effects of silicon in reducing the destructive effects of salinity-induced osmotic stress are shown in Fig. 3.

Balance of Nutrients

Salinity stress causes an imbalance of nutrients and the disruption of water uptake by plants. Silicon not only increases the absorption and transfer of K and reduces the absorption and transfer of Na and chlorine (Cl) from the roots to the shoots but also increases the absorption of P, N, Ca, and other essential nutrients (Pavlovic et al. 2021). The uptake of nutrients is related to the properties of the roots, including length and surface area; as root surface area increases, more space is provided for the uptake of dispersible ions (Vuyyuru et al. 2018). Many studies have reported a Si-induced increase in root growth under salinity stress (Basirat and Mousavi 2022; Mousavi 2022; Mushtaq et al. 2020, 2019), while other studies have shown that Si increases nutrient uptake by increasing root efficiency for water uptake (Basirat and Mousavi 2022; Mousavi 2022). The stimulating effect of Si on root growth in wheat and sorghum can be attributed to increased root elongation due to increased cell wall dilation in the growing area (Daoud et al. 2018; Hattori et al. 2003). Increased nutrient uptake may also be related to increased plasma membrane proton pump (H^+-ATPase) activity. For example, Kaya et al. (2006) have reported an increase in K and Ca absorption. There have been conflicting reports on the relationship between Si, P, and Zn uptake. Gao et al. (2005) found that the application of Si significantly reduced P concentration in the sapwood of maize. Eneji et al. (2008) found that Si increased P uptake by increasing P concentration in soil solution. Table 4 summarizes the different effects of Si on improving various parameters of wheat under salinity stress.

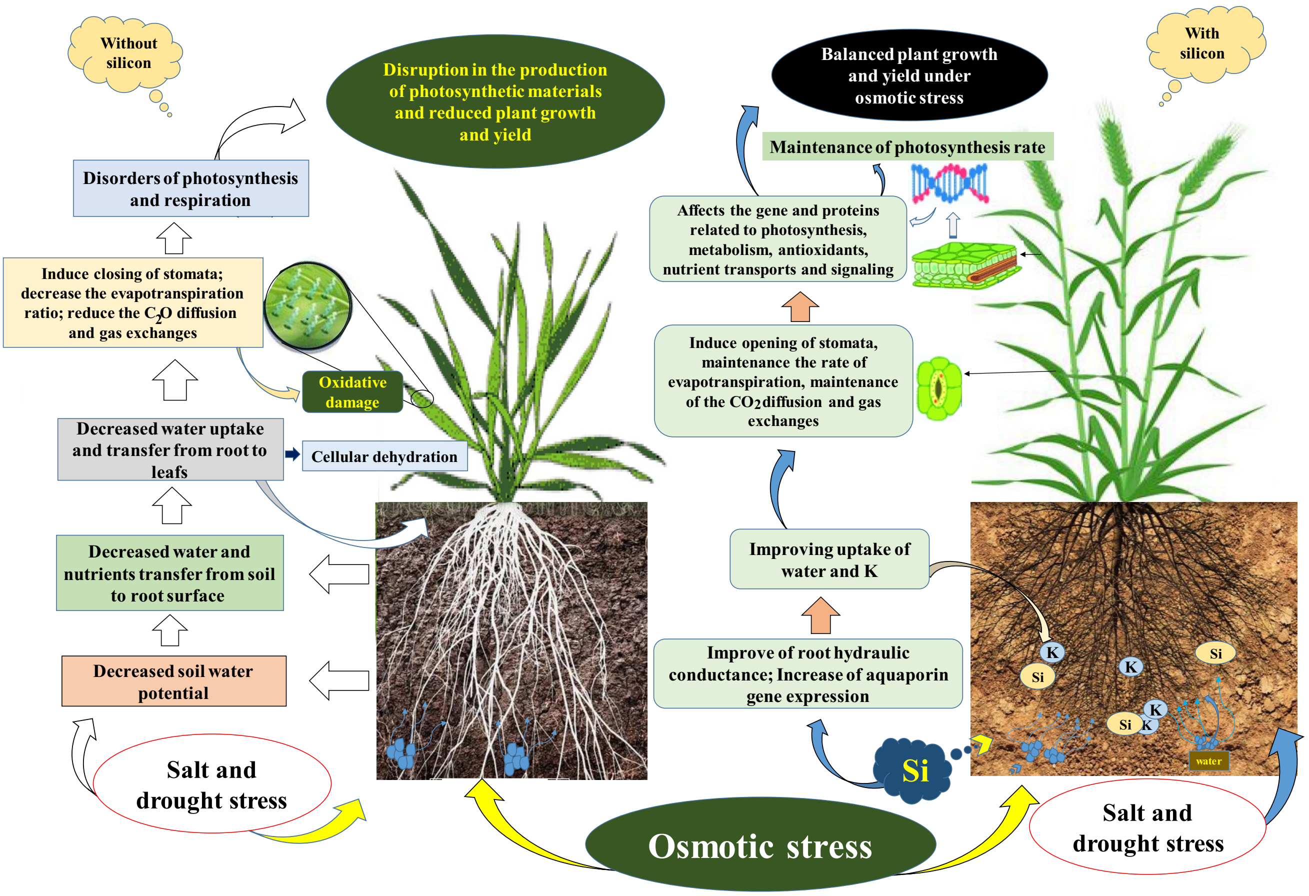

Fig. 3 The involved mechanisms by which Si alleviate osmotic stress affected by drought and salinity stress in wheat. For details, see the text (Sects. 3–1-6 and 3–2-5) and also these references (Tahir et al. 2006; Chen and Jiang 2010; Ahmad and Haddad 2011; Ali et al. 2012; Al-Bahrany and Al-Khayri 2012; Yin et al. 2013; Ahmad 2014; Liu et al. 2015; Singh et al. 2015; Taffouo et al. 2017; Zhang et al. 2017; Daoud et al. 2018; Walsh et al. 2018; Shams et al. 2019; Koenigshofer and Loeppert 2019; Thorne et al. 2021; Vandegeer et al. 2021; Akhter et al. 2021)

Conclusion and Suggestions

Since Si was recognized as a quasi-essential element for plants, many studies have investigated the effects of Si on various plants. Although most studies have shown positive roles for Si under stress conditions, there is some evidence that Si can improve the growth and yield of a wide range of plants under non-stress conditions. To date, there is little information about the effect of Si on plant metabolism. In many regions, Si has not been considered a fertilizer, even though it is beneficial to many crops, especially rice and wheat. In summary, more research work is warranted for the Si roles in the aspects listed below:

a) Most studies about the positive effects of Si on physiological and biochemical processes that contribute to wheat resistance to salinity and drought stresses have been done in greenhouses and controlled growth chambers. It is essential to investigate the effects of Si on crops under field conditions.
b) More attention is needed to evaluate the effectiveness of the Si-fertilizer formulation and its combination with other nutrients, as well as the best time to use it.
c) Knowledge is still limited about the role of Si in plant metabolic activity under different stresses, especially in the molecular aspects.
d) Few studies are reporting the potential of organic, biologic (Si-soluble bacteria), and nanoparticle (Si-NPs) sources of Si to alleviate drought and salinity stresses.

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Table 4 The beneficial effect of silicon on reducing the negative effect of salinity stress on various parameters of wheat

Parameters	Type of fertilizer	Application details	Observed effects of Si under stress conditions	Growth medium	Reference
Growth parameters	Calcium silicate	Nutrient solution (50, 100, 150 and 200 mg l^{-1})	Increase shoot growth (wet and dry weight and height) without affecting root growth	Hydroponic cultivation in plastic pots with sand culture medium	Ali et al. (2009)
	–	Nutrient solution (2 mM)	Increase plant growth and grain yield	Solution culture	Tahir et al. (2011)
	Potassium silicate	Foliar application (100 and 200 ppm)	Increase in weight of 100 seeds, and number of seeds per spike	Field culture	Salim et al. (2013)
	Potassium silicate	Nutrient solution (2 and 4 mmol l^{-1})	Increase ear length, thousand-grain weight, and final grain yield	Solution culture	Ahmad (2014)
	Na_2SiO_3	Application with nutrient solution (1 mM)	Increase the fresh weight of shoot and leaf area	Hydroponic culture in the 5-L plastic pots	Chen et al. (2014)
	rice hush ash (sio_2)	Mix with soil (1000, 2000, and 3000 kg ha^{-1}rice hush ash)	Increase the number of spikes and seed weight per plant, without significant effect on germination percentage	Potted cultivation in the soil culture medium in the greenhouse	Castellanos et al. (2016)
	Potassium silicate, silicic acid, and nano-silica	Application with nutrient solution (0.05 and 0.1 g l^{-1})	Increase in fresh and dry weight of shoots, increase in root and shoot length, increase in chlorophyll content	Hydroponic culture in nutrient solution	Mushtaq et al. (2019)
	Sodium silicate	Mix fertilizer with soil (100 mg kg^{-1})	Improving germination percentage, increasing height and dry weight of plant shoots under 100 Mm of NaCl salinity	Potted cultivation in soil and outdoors	Mushtaq et al. (2020)

Table 4 (continued)

Parameters	Type of fertilizer	Application details	Observed effects of Si under stress conditions	Growth medium	Reference
Uptake and accumulation of elements in the plant	Calcium silicate	ix fertilizer with soil (250 and 150 µg of Si per gram of soil)	Increase potassium uptake, decrease Na uptake and transport, increase potassium-to-Na ratio in shoots	Cultivation in potting soil	Tahir et al. (2006)
	Sodium silicate	Nutrient solution (0.25 and 0.5 mM)	Increasing potassium concentration and decreasing Na concentration in roots and shoots	Solution culture	(Tuna et al. (2008)
	Silicic acid	Add Si to the nutrient solution (1 mM)	Decrease Na absorption, increase Na binding to the cell wall, increase potassium uptake, increase potassium-to-Na ratio	Hydroponic culture in the 1-L pots containing Hoagland	Saqib et al. (2008)
	Calcium silicate	Nutrient solution (50, 100, 150 and 200 mg l^{-1})	Increase potassium uptake, decrease Na uptake, increase potassium-to-Na ratio	Hydroponic cultivation in plastic pots with sand culture medium	Ali A et al. (2009)
	–	Nutrient solution (2 mM in 2011 and 2012 and 2 and 4 mM in 2010)	Increasing K concentration and decreasing Na concentration in shoots	Solution culture	Tahir et al. (2012)
	Calcium silicate	Application with the nutrient solution (150 mg l^{-1})	Increase potassium uptake, decrease Na uptake, increase potassium-to-Na ratio	Hydroponic cultivation in pots with a sand culture medium	Salim et al. (2013)
	Potassium silicate	Foliar application (100 and 200 ppm)	Increase uptake of N, Kand phosphorus in the plant, decrease uptake of Na, and increase the ratio of K to Na	Cultivation in the farm	Salim et al. (2013)
	Sodium silicate	Application with a nutrient solution (1 mM)	Decrease Na concentration in the leaves	Hydroponic culture in the 5-L plastic pots	Chen et al. (2014)
	Potassium silicate	Nutrient solution (2 and 4 mmol l^{-1})	Increase potassium uptake and decrease Na uptake	Solution culture	Ahmad (2014)
	Na metasilicate	Irrigation fertilizer with nutrient solution (0.75 mM)	Increasing the amount of potassium and decreasing Na in the leaves, and finally increasing the ratio of potassium to cytosolic Na	Cultivation of plants in pots with sand culture medium, hydroponic	Daoud et al. (2018)
	Calcium silicate	Application with a nutrient solution (6 mM)	Increase potassium uptake, decrease Na uptake, increase potassium-to-Na ratio	Hydroponic cultivation in pots	(Ali et al. (2019)

Table 4 (continued)

Parameters	Type of fertilizer	Application details	Observed effects of Si under stress conditions	Growth medium	Reference
Activities of antioxidant enzymes and reactive oxygen species (Effect on oxidative stress)	Calcium silicate	Application with the nutrient solution (150 mg l^{-1})	Increase superoxide dismutase and catalase activity and decrease electrolyte leakage and H_2O_2 activity	Hydroponic cultivation in pots with a sand culture medium	Ali A et al. (2012)
	Sodium silicate	Application with the nutrient solution (3 mM)	Increase activity of antioxidant enzymes	Hydroponic culture	Gurmani et al. (2013)
	Sodium silicate	Irrigation fertilizer with nutrient solution (0.75 mM)	Increasing the activity of superoxide dismutase, catalase, and decreasing H_2O_2 in the booting stage of wheat	Cultivation of plants in pots with sand culture medium	Daoud et al. (2018)
	Potassium silicate	Irrigation fertilizer (2, 4, and 6 mM)	Increase superoxide dismutase, catalase, peroxidase activity. and decrease electrolyte deposition and malondialdehyde activity	Cultivation in potting soil in the greenhouse	Alzahrani et al. (2018)
	Calcium silicate	Application with nutrient solution (6 mM)	Increase superoxide dismutase and catalase activity	Hydroponic cultivation in pots	Ali A et al. (2019)
Gas exchange and photosynthesis	Sodium silicate	Nutrient solution (0.25 and 0.5 mM)	Increase in chlorophyll a and b and total chlorophyll	Solution culture	Tuna et al. (2008)
	–	Nutrient solution (2 mM)	Increase chlorophyll content in leaves	Solution culture	Tahir et al. (2012)
	Sodium silicate	Application with nutrient solution (3 mM)	Increase photosynthetic gas exchange (net assimilation rate and stomatal conductance)	Hydroponic culture	Gurmani et al. (2013)
	Sodium metasilicate	Irrigation fertilizer (0.75 mM)	Increase in chlorophyll a and b and carotenoids (total photosynthetic pigments) in the boot stage of wheat	Hydroponic cultivation in pots with a sand culture medium	Daoud et al. (2018)
	Calcium silicate	Application with nutrient solution (6 mM)	Increase in total chlorophyll content and chlorophyll a/b ratio in leaves	Hydroponic cultivation in pots	Ali A et al. (2019)

Table 4 (continued)

Parameters	Type of fertilizer	Application details	Observed effects of Si under stress conditions	Growth medium	Reference
Water relations	–	Nutrient solution (2 mM)	Maintain membrane permeability and improve water condition	Solution culture	Tahir et al. (2012)
	Sodium silicate	Application with nutrient solution (3 mM)	Increase water use efficiency (WUE)	Hydroponic culture	Gurmani et al. (2013)
	Potassium silicate	Application with nutrient solution (1 and 4 mM)	Reduce the osmotic potential in the roots and ultimately increase the water uptake capacity by the roots	Hydroponic culture in pots containing nutrient solution	Hajiboland et al. (2017)
	Potassium silicate	Irrigation fertilizer (2, 4, and 6 mM)	Increase relative water content (RWC%) and increase membrane stability index (MSI)	Cultivation in potting soil in the greenhouse	Alzahrani et al. (2018)
Osmoprotectants	Sodium silicate	Nutrient solution (0.25 and 0.5 mM)	Decrease membrane permeability and proline content in leaves	Solution culture	Tuna et al. (2008)
	Silicic acid	Application with nutrient solution (1 mM)	Increase glutathione concentration	Hydroponic culture in pots containing Hoagland	Saqib et al. (2008)
	Potassium silicate	Foliar application (100 and 200 ppm)	Increasing the concentration of biochemical compounds (phenols, proteins and proline)	Cultivation on the farm	Salim et al. (2013)
	Potassium silicate	Application with nutrient solution (1 and 4 mM)	Increases the amount of soluble sugars, proteins, and free amino acids (especially proline) in the leaves	Hydroponic culture in pots containing nutrient solution	Hajiboland et al. (2017)
	Potassium silicate	Irrigation fertilizer (2, 4, and 6 mM)	Increased levels of soluble sugars, free proline, glutathione, and ascorbic acid	Cultivation in potting soil in the greenhouse	Alzahrani et al. (2018)

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Declarations

Conflict of interest On behalf of all authors, the corresponding authors state that there is no conflict of interest.

Research Involving Human Participants and/or Animals Not applicable.

Consent to Participate Not applicable.

Consent for Publication In accordance with the copyright transfer or open access rules.

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