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CHAPTER
[14]

Strategies to prevent environmental stresses by silicon fertilization in rice crop

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ABSTRACT

Rice is the most important staple food crop for a large part of the world's population, especially in East and South Asia, Middle East, Latin America, and the West Indies. As the population increases rapidly in these regions, the demand for rice will grow to an estimated 2000 million metric tons by 2030. To supply to this increasing demand, the methods of rice production will require significant improvement. Achieving this goal, however, is sure to be a challenge with respect to future climatic changes, which will basically be characterized by current global warming trends. The rise in temperatures and levels of carbon dioxide and uncertain rainfall associated with climate change may have serious adverse effects either directly or indirectly on the growth, development, and yield of rice crops. To cope with the unfavorable growth conditions, plants respond with a series of morphological, biochemical, and molecular adaptations, aiming at safeguarding the basic metabolic activities. All the unfavorable factor which limit crop yield may be consider as a stress. Silicon seems to protect plants from such types of stresses caused by environmental degradation. This can be managed by proper agronomic practices or developing resistance variety. Therefore, in this chapter we showed that how we can manage these stresses to boost rice productivity in changing climatic scenario while using silicon fertilizer as a protective agent.

KEYWORDS

Climate change, Environmental stress, Global warming, Rice crop, Productivity

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Introduction

Stress is an external factor that decreases crop yields from yield maximum to a lower level for examples diseases, insects, salinity, and excesses of trace elements. Due to global warming, and potential climate abnormalities associated with it, crops typically encounter an increased number of abiotic and biotic stress combinations, which severely affect their growth and yield (Ramegowda and Kumar, 2015; Kumar *et al*., 2020). Concurrent occurrence of abiotic stresses such as drought and heat has been shown to be more destructive to crop production than these stresses occurring separately at different crop growth stages (Prasad *et al*., 2011). Abiotic stress conditions such as drought, high and low temperature and salinity are known to influence the occurrence and spread of pathogens, insects, and weeds (Peters *et al*., 2014). They can also result in minor pests to become potential threats in future. These stress conditions also directly affect plant–pest interactions by altering plant physiology and defense responses. Additionally, abiotic stress conditions such as drought enhance competitive interactions of weeds on crops as several weeds exhibit enhanced water use efficiency than crops (Valerio *et al*., 2013). Abiotic stresses like salinity, water deficit, chilling, and heavy metals adversely affect the growth and several physiological processes of plants. In general, low temperature mainly results in mechanical constraint, whereas salinity and drought exert their malicious effect by disrupting the ionic and osmotic equilibrium of the cell. The detrimental effects of excess salts are the consequences of water deficit that results from decreased osmotic/water potential of soil solution due to high solute concentration in the soil, as well as ion-specific stresses due to altered Na^+/K^+ ratios and Na^+/Cl^- ratios that are inimical to the plants. The phytohormone abscisic acid (ABA) regulates desiccation tolerance in seeds as well as in vegetative tissue. The endogenous ABA concentration increases in different plant tissues during drought, salinity, or cold induced oxidative stress. To cope with the unfavorable growth conditions, plants respond with a series of morphological, biochemical, and molecular adaptations, aiming at safeguarding the basic metabolic activities. It is now well known that the stress signal is first perceived at the membrane level by the receptors and then transduced into the cell to switch on the stress responsive genes for mediating stress tolerance. Population growth and water scarcity combined mean that there is no alternative but induced by drought, high salinity, and low temperature stresses, and their products are thought to function in stress tolerance and response (Roychoudhury *et al*., 2013).

Environmental factors responsible stress in rice crop

Droughts

Drought is generally avoided in areas where irrigation water is available throughout the season, but it is a consistent feature across much of the 63.5 million hectares of rainfed rice sown annually, most of which is in tropical Asia, Africa and Latin America. It can occur at any stage during the rice cropping season, but it is more devastating when it occurs just prior to flowering than it is during the vegetative stage, with substantial effects on grain yield. About 70% of the rice area in sub- Saharan Africa is rainfed. The spatial and temporal variability of rainfall in this region expose rice plants to frequent drought spells. Regardless of the total rainfall and distribution, the poor physical properties of highly weathered, coarse-textured soils in some parts of sub-Saharan Africa induce low water-holding capacity and establish water deficit as a major constraint to rainfed crop yields in sub-Saharan Africa. This is particularly true for upland rice, which makes up 32% of rice-growing areas in sub-Saharan Africa. Analysis of farmer perceptions in 18 countries in sub-Saharan Africa across rice environments provided evidence that in 2008 an estimated 10% of rice farmers experienced drought affecting 37% of their rice area, causing 29% of rice yield loss. The diversity of affected production systems, variability of drought in terms of timing and severity, and the multiple traits involved in drought tolerance require strategic research to prioritize and define environment-specific approaches for developing drought-tolerant rice cultivars.

Submergence and water logging

Rice plants require water for growth but excess water that occurs during submergence or water logging is harmful or even lethal. A submerged plant is defined as "a plant standing in water with at least part of the terminal above the water or completely covered with water" (Catling, 1992). Submergence subjects plants to the stresses of low light, limited gas diffusion, effusion of soil nutrients, mechanical damage, and increased susceptibility to pests and diseases (Ram *et al.*, 1999). Basically, flooding (i.e., submergence) can be classified into "flash flooding" and "deepwater flooding" in accordance with the duration of flooding and the water depth. Flash flooding, which generally lasts less than a few weeks, is caused by heavy rain but the depth is not very deep. On the other hand, deepwater flooding, which lasts for several months, occurs during the rainy season, and the water depth reaches several meters (Hattori *et al.*, 2011). Water logging is defined as a condition of the soil in which excess water limits gas diffusion (Setter and Waters, 2003). Oxygen diffusivity in water is approximately 10,000 times slower than in air, and the flux of O_2 into soils is approximately 320,000 times less when the soil pores are filled with water than when they are filled with gas (Colmer and Flowers, 2008). The principal cause of damage to plants grown in waterlogged soil is inadequate supply of oxygen to the submerged tissues as a result of slow diffusion of gases in water and rapid consumption of O_2 by soil microorganisms. Oxygen deficiency in waterlogged soil occurs within a few hours under some conditions. In addition to the O_2 deficiency, production of toxic substances such as Fe^{2+}, Mn^{2+}, and H_2S by reduction of redox potential causes severe damage to plants under waterlogged conditions (Setter *et al.* 2009).

Soil salinity

Irrigation has the potential to ensure high rice yields and is a good strategy to offset recurrent droughts. Unfortunately, soils of most irrigated areas have continued to be degraded as a result of poor irrigation practices and the absence of efficient drainage. These have led to a rapid rise in the water table and an increase in soil sodium/alkalinity and salinity (Bertrand *et al.*, 1993). In the Office du Niger (Mali), 50% of the water table is now saline and occasionally very saline despite low mineral content of the irrigation water (Bertrand *et al.*, 1993). In the Senegal River delta, marine-derived soil salinity is an inherent problem and sodicity is increasing in irrigated flood plains in inland areas due to high evaporation, rising groundwater tables and poor drainage (Matlon *et al.*, 1998). Miézan and Dingkuhn (2001) observed that waters of the Niger and Senegal rivers carry substantial alkalinity, and the salt content of water sometimes increases markedly between the main rivers and the actual irrigation site. However, van Asten *et al.* (2003) show that salt accumulation in the soils of Sahelian countries has more to do with the underlying bedrock than with the irrigation system. Examining soils in the irrigated areas of Foum Gleita (Mauritania) they found that the geographical distribution of salt was not related to the presence of irrigation or drainage canals. Also the alkaline salts present in the upper soil layers in Foum Gleita did not come from irrigation water, but from the underlying bedrock. Additional to the salt stress itself, the high pH resulting from the sodification/ alkalinization reduces the availability of plant nutrients such as zinc and increases nitrogen losses through volatilization (Miézan and Dingkuhn, 2001). However, salinity tolerance at these two stages is only weakly associated (Moradi *et al.*, 2003). Discovering and combining suitable tolerance traits for both stages is essential for developing resilient salt-tolerant varieties. Moreover, the salt-tolerance level of cultivars depends on environmental conditions (Asch *et al.*, 1997). Generally, salinity effects on rice are more severe in arid climates than in humid ones. For example, salinity levels at an electric conductivity (EC) of 9.5 mS/ cm were reported to cause a 50% yield loss in the humid tropics (Flowers and Yeo, 1981), whereas under the arid conditions of the Sahelian dry season an equivalent yield loss was observed at an EC of only 3.5 mS/cm (Dingkuhn *et al.*, 1993).

Role of silicon in enhancing the resistance to environmental stresses

Silicon and rice blast disease

The suppressive effect of Si on rice blast was reported as early as 1917 by Onodera (1917). Rice blast, caused by *Magnaporthe grisea*, is the most destructive fungal disease of rice, particularly in temperate, irrigated rice and tropical upland rice. The pathogen can infect all the above-ground parts of the rice plant, but occurs most commonly on leaves causing leaf blast during the vegetative stage of growth or on neck nodes and panicle branches during the reproductive stage, causing neck blast (Bonman *et al.,* 1989). Silicon reduces the epidemics of both leaf and panicle blast at different growth stages. In Florida, where soil is deficient in Si, application of silicate fertilizer is as effective as fungicide application in controlling rice blast (Datnoff *et al.,* 1997). Rice seedling blast is significantly suppressed by the application of Si fertilizers in the nursery (Maekawa *et al.*, 2001).

Silicon and powdery mildew disease

Silicon has been reported to prevent the incidence of powdery mildew disease, which is caused by *Sphaerotheca juliginea*, in a number of plant species. Miyake and Takahashi (1983) reported that by increasing the Si concentration in the culture solution, the Si content in the cucumber shoot increased, resulting in a reduced incidence of powdery mildew disease. In strawberry, when the Si content of leaves increased proportionally to the increase of the Si concentration in the culture solution, the incidence of powdery mildew decreased (Kanto, 2002). Silicon deficiency in barley and wheat leads to a poor growth habit and increased powdery mildew susceptibility (Zeyen, 2002). Menzies *et al.* (1991) found that infection efficiency, colony size, and germination of conidia were reduced when cucumbers were grown in nutrient solutions with high concentrations of Si. Foliar application of Si has been reported to be effective in inhibiting powdery mildew development on cucumber, muskmelon, and grape leaves (Bowen *et al.,* 1992). Si applied to leaves may deposit on the surface of leaves and playa similar role to that of Si taken up from the roots.

Silicon and other diseases

In addition to blast and powdery mildew, the occurrence of brown spot, stem rot, sheath brown rot on rice, fusarium wilt, and corynespora leaf spot on cucumber decreased by increasing the Si supply. In turfgrass, several diseases were also suppressed by Si application (Datnoff *et al.,* 2002). Rice bacterial blight caused by *Xanthomonas oryzae* pv. oryzae (Xoo) is a serious disease worldwide. Chang *et al.* (2002) reported that in the cultivar TNI which is susceptible to this disease the Si content in leaves was lower than that of the resistant breeding line, TSWY7 under the nutrient cultural system adopted. The degree of resistance to this disease increased in parallel with the increased amount of applied silicon. Si-induced decrease of soluble sugar content in the leaves seems to contribute to the field resistance of the disease. Silicon is also effective in increasing the resistance to the fungal diseases caused by *Pythium ultimum* and *Paphani dermatum* in cucumber roots (Cherif *et al.,* 1994).

Silicon and pests

Silicon suppresses insect pests such as stem borer, brown plant hopper, rice green leaf hopper, and white backed plant hopper, and non insect pests such as leaf spider and mites (Savant *et al.*, 1997). Stems attacked by the rice stem borer were found to contain a lower amount of Si (Sasamoto, 1961). In a field study, a positive relationship between the Si content of rice and resistance to the brown plan thopper has been observed (Sujatha *et al.*, 1987).

Possible mechanisms involved

Two hypotheses for the Si-enhanced resistance to diseases and pests have been proposed. One is that Si deposited on the tissue surface acts as a physical barrier. It prevents physical penetration and / or makes the plant cells less susceptible to enzymatic degradation by fungal pathogens. This mechanism is supported by the positive correlation between the Si content and the degree of suppression of diseases and pests. The other one is that Si functions as a signal to induce the production of phytoalexin (Cherif *et al.,* 1994). Si application to cucumber resulted in the stimulation of the chitinase activity and rapid activation of peroxidases and polyphenol oxidases after infection with Pythium spp. Glycosidically bound phenolics extracted from Si-treated plants when subjected to acid or Β-glucosidase hydrolysis displayed a strong fungistatic activity. However, in oat attacked by *Blumeria graminis*, Si deficiency promoted the synthesis of phenolic compounds (Carver *et al.*, 1998).

The phenylalanine ammonia-lyase activity was enhanced by Si deficiency. The reason why Si deficiency exerts opposite effects on the synthesis of phenolic compounds, as a disease response in different plant species, has not been elucidated. Recently, Kauss *et al.* (2003) have reported that during the induction of systemic all acquired resistance (SAR) in cucumber, the expression of a gene encoding a novel proline-rich protein was enhanced. This protein has C-terminal repetitive sequences containing an unusually high amount of lysine and arginine. The synthetic peptide derived from the repetitive sequences was able to polymerize orthosilicic acid to insoluble silica, which is known to be involved in cell wall reinforcement, at the site of the attempted penetration of fungi into epidermal cells.

Silicon and radiation damage

Silicon seems to protect plants from radiation injury. When rice seedlings (30-days old) were irradiated with different doses of γ-rays, the decrease in the dry weight was less appreciable in the Si-supplied plants than in the Si plants that had not been treated with Si, suggesting that Si increases the resistance of rice to radiation stress (Takahashi, 1966). Furthermore, when the plant was supplied with Si after radiation treatment, the growth recovery was faster compared to that of the plants without Si supply.

Silicon and water stress

Water deficiency (drought stress) leads to the closure of stomata and subsequent decrease in the photosynthetic rate. Silicon can alleviate water stress by decreasing transpiration. Transpiration from the leaves occurs mainly through the stomata and partly through the cuticle. As Si is deposited beneath the cuticle of the leaves forming a Si-cuticle double layer, the transpiration through the cuticle may decrease by Si deposition. Silicon can reduce the transpiration rate by 30% in rice, which has a thin cuticle (Ma *et al.*, 2001). Under water-stressed conditions (low humidity), the effect of Si on rice growth was more pronounced than on rice that cultivated under non-stressed conditions (high humidity) (Ma *et al.*, 2001). When rice leaves were exposed to a solution containing polyethylene glycol (PEG), electrolyte leakage (EL) (an indicator of membrane lesion) from the leaf tissues decreased with the increase in the level of Si in the leaves (Agarie *et al.*, 1998). The level of polysaccharides in the cell wall was higher in the leaves containing Si than in those lacking Si. These results suggest that Si in rice leaves is involved in the water relations of cells, such as mechanical properties and water permeability. Among the yield components, the percentage of ripened grains is most affected by Si in both rice and barley (Ma and Takahashi, 2002). This function of Si may be attributed to the alleviative effect of Si on water stress. One important factor for the normal development of the spikelets is to keep a high moisture condition within the hull (Seo and Ohta, 1982). The Si content in the hull of the rice grain becomes as high as 7% Si and that of the barley grain is 1.5%. Silicon in the hull is also deposited between the epidermal cell wall and the cuticle, forming a cuticle-Si double layer as in the leaf blades. However, in contrast to the leaves, transpiration occurs only through the cuticle because the hull does not have a stoma. Silicon is effective in decreasing the transpiration from the hull. The rate of water loss from Si free spikelet's was about 20% higher than that from spikelet's containing Si (7% Si) at both the milky and maturity stages (Ma *et al.*, 2001). Therefore, Si plays an important role in keeping a high moisture condition within the hull by decreasing the transpiration rate from the hull. This is especially important under water deficiency stress and stress associated with climatic conditions.

Silicon and stress associated with climatic conditions

Silicon application in rice is effective in alleviating the damage caused by climatic stress such as typhoons, low temperature and insufficient sunshine during the summer season (Ma and Takahashi, 2000). A typhoon attack usually causes lodging and sterility in rice, resulting in a considerable reduction of the rice yield. Deposition of Si in rice enhances the strength of the stem by increasing the thickness of the culm wall and the size of the vascular bundles (Shimoyama, 1958), thereby preventing lodging. Strong winds also cause excess water loss from the spikelets, resulting in sterility. Silicon deposited on the hull is effective in preventing excess water loss.

In addition, the effect of Si on the rice yield is also obvious under stress due to low temperatures and insufficient sunshine (Ma and Takahashi, 2002).

Silicon and heat stress

Silicon also increases the tolerance to heat stress in rice plants. Agarie *et al.* (1998) observed that electrolyte leakage caused by high temperature (42 °C) was less pronounced in the leaves grown with Si than in those grown without Si. These results suggest that Si may be involved in the thermal stability of lipids in cell membranes although the mechanism has not been elucidated.

Conclusion

Si enhanced resistance to diseases and pests. Si deposited on the tissue surface acts as a physical barrier. It prevents physical penetration and / or makes the plant cells less susceptible to enzymatic degradation by fungal pathogens. It provides strength to the stem by increasing the thickness of the culm wall and the size of the vascular bundles. Si is deposited beneath the cuticle of the leaves forming a Si-cuticle double layer which act as barrier for insect and pest attack it also reduces the transpiration losses. Thus it can be concluded that Si has the capacity to provide resistance against environmental stress for the better growth and development of rice plant.

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