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ROLE OF SILICON APPLICATION IN THE AUGMENTATION THE PLANT RESISTANCE UNDER FLUORIDE STRESS: A REVIEW

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Review Article

ABSTRACT

Salinity stress, mainly elevated levels of fluoride affects the growth and development of crop plants which causes huge decline in crop yield. Salinity stress decreases the chlorophyll pigments concentration hence reduces photosynthetic rate resulting into poor plant growth. Fluoride induced accumulation of ROS leads to oxidative stress which adversely affects plant metabolism. In plants, the attainment of salt tolerance via breeding method is difficult due to complexity and polygenic nature of salt tolerance traits. Hence, silicon application is one of the preferred approaches that have potential mitigate the adverse effect of salinity stress, especially fluoride in eco-friendly way. In this review an attempt is made to enhance the understanding in all-inclusive way.

Keywords: Fluoride toxicity; plant stresses; resistance; silicon.

INTRODUCTION

Plants are exposed to different abiotic and biotic stresses, *viz*., high salt, temperature, drought, cold, and pathogen infections. Abiotic stresses alone caused loss of more than 50% of crop yield throughout the world. Among the abiotic stresses, salinity causes severe loss in crop yield due to impaired metabolism and reduction in protein synthesis. In the commencement, salinity stress shows hyper-ionic and hyper-osmotic effects that cause oxidative stress in plants [1]. Plant growth under saline environment shows intricate modulations in normal mechanisms resulting in changes in metabolism, physiology and morphology of plant that leads to decrease yield and retard growth in plants [2].

Fluoride is one of the abiotic stresses, which causes toxic effects not only in humans and domestic animals but also in plants [3]. Fluoride is considered the 13th most prevalent element of the earth's crust. Fluoride occurs naturally in the form of HF or NaF where they are present in soil. Fluoride ion spread into the surroundings through emissions of volcanic ash, weathering of minerals and marine aerosols [4]. Hence, fluoride is a widely distributed, non-biodegradable and harmful non-metal pollutant [5]. From soil, fluoride is absorbed through xylem flow and transported to the aerial parts of the plant like leaves. Fluoride accumulates in these organs and cause toxic effects in plant, consequently several changes at biochemical, morphological and physiological levels in plant occur that affect the overall growth and development of plant.

Fluoride affects various physiological processes of plant growth, *viz*., leaf chlorosis, necrosis and leaf tip burn [6]. Fluoride is known as potential metabolic inhibitor, which interferes with overall responses of plants including seed germination, growth and productivity, biomass accumulation, enzyme activities, photosynthesis, protein synthesis and secretion, pattern of gene expression, and formation of ROS (Reactive Oxygen Species) [7,8]. Fluoride affects the rate of photosynthesis by degrading the ultrastructure of chloroplast [9]. Yadu et al. (2016) examined the changes in the activities of antioxidant enzymes like CAT (catalase), SOD (superoxide dismutase), POD (peroxidase), GR (glutathione reductase) and GSH (Glutathione) [10]. Due to fluoride toxicity, enzyme activities get altered that cause changes in growth, development and reproduction in plant [11]. Various chemical, biological and physical (engineering) approaches are used to increase the crop productivity under the salinity stress. However, it would be a better approach to overcome negative effect of salinity stress by exogenous application of nutrients. Silicon is one of them which can be a useful element for normal growth of plants under fluoride stress [2].

Silicon (Si) is second most abundant element in soil [12]. Si is a beneficial element in plants and a crucial necessity of many plants for normal growth and must be called as “Quasi-essential” [2]. Si is only nutrient element, which is not detrimental while absorbing excess in plants [13]. Moreover, Si enhancing the mechanical support by strengthens cell walls through augmenting lignification, suberization and silicification [14]. Bio-silicification in plant develop silica barrier, which act as primary defense against abiotic and biotic stresses [15]. It has been studied that Si is useful for the growth of many plants under different abiotic (such as metal toxicity, salt and drought) and biotic (such as pest and plant diseases) stresses [16,17].

Several attempts have been made in past in this aspect, for instance, addition of Si mitigates harmful effects of salinity stress on Mung beans by the alteration in the inorganic nutrients uptake, production of osmolyte and the antioxidant defense system [18]. Various mechanisms are studied which revealed that Si may enhance salt tolerance in plants such as enhance plant water status [19], maintenance of ultrastructure of leaf organelles and increase activity of photosynthesis [20] and stimulation of ROS scavenging system [21]. Addition of silicon improved the ultrastructure of chloroplasts that were injured by the addition of salt [22]. It has also been reported that silicon addition significantly increases defensive enzymes, *viz*., SOD, POD, CAT, and GR activities and decrease LPO (lipid peroxidation) in barley plant [23].

In this article, the plant responses to saline environments have been reviewed and fluoride-induced damages to plants have also been discussed. The role of silicon to alleviate the salinity induced damages in plants is documented and the roles of Silicon to mitigate the fluoride induced damages have been analytically brushed up.

EFFECT OF SALT (MAINLY FLUORIDE) STRESS ON MORPHOLOGICAL, PHYSIOLOGICAL AND BIOCHEMICAL PROCESSES

Germination

Rehman et al. [24] reported that salinity stress has harmful correlation with seed germination. Khan and Weber [25] reported that salt stress at high level inhibits the seed germination whereas at low level of salt stress induces a dormancy state. Relationship between germination rate and time after sowing at distinctive level of salt has been observed (Fig. 1). High salinity showed less percentage of germination rates [26]. High concentration of salt in germination media significantly delays onset and decrease germination rate in *Solanum lycopersicum* L. [27,28]. Increase in the concentration of NaCl gradually retarded and decreased the rate of germination in *Hordeum spontaneum* L. [29]. In the seeds of *Zea mays* L., when exposed to NaCl showed extreme reduction in the germination rate, radicle and plumule length, length of seedling and seed vigor [30].

Sabal et al. [31] experimentally studied fluoride stress on *Cyamopsis tetragonoloba* [L.] Taub. (cluster bean*)* seed germination and seedling growth. Seed germination and seedling growth was adversely affected by NaF concentration. Chakrabarti et al. [32] experimentally studied NaF (Sodium Fluoride) effect on germination of seed, seedling growth and biochemistry of Bengal gram.

Growth and Development

Garber [33] experimentally studied that 1000 to 1500 ppm of fluoride added to soil leads to reduce wheat yield about 65% and 400ppm decrease *Tradescantia* Ruppius ex L. growth by 28 – 34%. Cooke [34] experimentally studied fluoride effect on common sunflower (*Helianthus annuus* L.). At 200ppm concentration, dry weight is not affected while leaf growth showed significant reduction. MacLean and Schneider [35] examined wheat plants (*Triticum aestivum* L.) exposed to 0.9µg F.m^{-3} for 4 days cause decrease (20%) in the mean dry mass.

Elrashidi et al. [36] reported that 100ppm fluoride significantly decrease dry matter yield of barley (*Hordeum vulgare* L.) grown in acidic (pH 4.75) and neutral (pH 6.6) soil about 40 days. While plants grown on alkaline soil (pH 7.5) remain unaffected at 1000 ppm of fluoride. Stevens et al. [37, 38] compare the effect of NaF in both *Lycopersicon esculentum* Mill. and *Avena sativa* L. At varying NaF concentrations from 1 to 128 ppm, both plants grew in nutrient solutions about 12-13 days and observe that F ion concentration more than 28ppm leads to decrease dry weights in shoots and roots

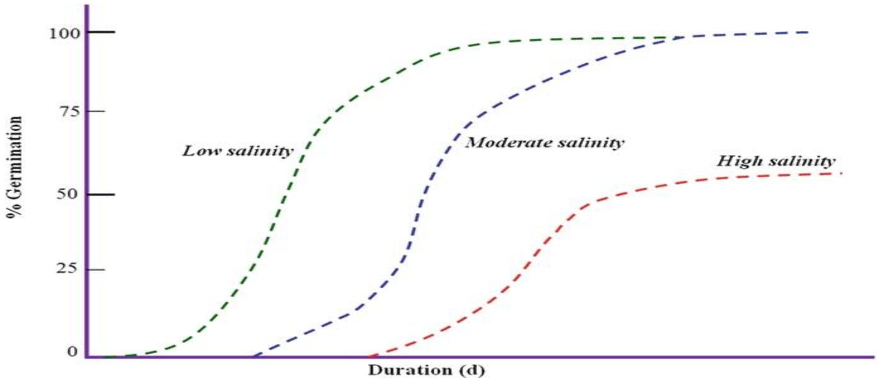

Fig. 1. Relationship between germination rate and time after sowing at distinctive salt levels (adopted from Lauchli and Grattan, 2007) [26]

of tomato, whereas exposure to all F concentrations in oat plants remains unaffected.

Sabal et al. [31] experimentally studied the fluoride on germination of seed, seedling growth and total biomass of cluster bean (*Cyamopsis tetragonoloba* [L.] Taub) at 0 to 30µM NaF concentration. As fluoride concentration increases, reduction in seed germination percent, length of root and shoot and total biomass observed after 15 days of treatment. 100 percent mortality of seeds observed at 30µM NaF concentration. Bhargava and Bhardwaj [6] experimentally studied fluoride effect on *Triticum aestivum* at different concentration. With increased in NaF concentration, length and dry weight of both root and shoot decreased. Datta et al. [39] experimentally studied the effect of fluoride (0, 0.1, 0.5, 1.0, 4.0, and 8.0 mM) in gram seeds on seed germination, seedling growth under laboratory conditions. With increased in F concentration, the total soluble sugar content, peroxidase activity, proline content, ascorbic acid oxidase activity, phytotoxicity of shoot and root increased.

Gadi [40] experimentally studied the influence of 0.1, 0.25, 0.50, 0.75 and 1.0mM sodium fluoride (NaF) concentration on germination behavior, stability of membrane and several biochemical parameters in in-vitro grown *Vigna radiata* L., seedlings. Rate of germination, length of shoot and root, vigour index, membrane stability index, percent of chlorophyll stability index and soluble protein content were decreased whereas proline and carbohydrates increased in seedlings after 7 days of treatment under fluoride stress.

Yield

Salinity cause major loss in plants crop mostly in arid and semi-arid parts of the world [41]. Chakrabarti et al. [32] experimentally examined sodium fluoride effect on germination rate, growth of seedling and biochemistry of Bengal gram. Fluoride affects morphological as well as biochemical characteristic of Bengal gram. It also affects the crop quality and crop yield. It accumulates mostly in edible parts of plant due to translocation from root to shoot.

Photosynthesis

Tuna et al. [42] experimentally studied the cause of salinity stress on photosynthetic rate in tomato plant. Salinity stress decreases the chlorophyll pigments concentration that reduces photosynthetic rate and cause poor plant growth. Decrease in the concentration of chlorophyll leads to damage the chloroplast membrane that may improve permeability of membrane or loss of membrane integrity. Baunthiyal and Ranghar [9] demonstrated that fluoride affect rate of photosynthesis by reducing chlorophyll synthesis or by degrading the ultrastructure of chloroplast and an inhibition of Hill reaction. It has been reported that fluoride accumulates in chloroplast and affect the activities of RUBISCO, sucrose synthase, sucrose synthetase and enzyme associated with CO_2 fixation [43,44]. Saleh and Abdel-Kader [45] reported that fluoride cause harmful effect on photosynthesis pigment such as chlorophylls-a and b, carotenoids, and anthocyanins. High fluoride concentration decreases the availability of Fe^{2+} ions that are important for chlorophyll synthesis. Due to less availability of Fe^{2+} ions, activity of chlorophyll degrading enzyme increases which adversely affect the process of photosynthesis. It has also been reported that fluoride cause substitution of Cl^- ions in the photosystem-II by F which inhibit photo-oxidation of water. It leads to the generation of new free radical in proteins of this system that free radical is not compensate by the process of photolysis.

Oxidative Stress

Salt stress in plants leaves cause closure of stomata that leads to lower the CO_2/ O_2 ratio and cause CO_2 fixation inhibition. Therefore, ROS like Hydrogen peroxide, Superoxide radical, singlet oxygen and Hydroxyl radical increases that naturally formed in various cellular metabolic pathways like fatty acid oxidation, photosynthesis, photorespiration and senescence. ROS are generally formed within the mitochondria and chloroplast as well as from other pathways like photorespiration, chlorophyll degradation that attack on many cellular components such as photosynthetic pigments, lipids, nucleic acids and proteins and cause leaf chlorosis and necrosis [41]. Plants developed own defense mechanism for scavenging ROS to defend against cellular damage that contain enzymatic such as APX (ascorbate peroxidase), CAT and SOD and non-enzymatic antioxidants such as AsA (reduced ascorbate) and GSH [46]. Antioxidant enzymes (APX, CAT, SOD and GR) activities increases in salt stress have been studied into some plants like *Triticum aestivum* L. [47], *Brassica juncea* L. [48], *Solanum lycopersicum* L. [49], *Morus alba* L. [50] and *Cicer arietinum* L. [1]. It has been studied that antioxidants suppress the ROS that defend cells from oxidative injury cause through salt stressed [48,51].

Tak and Asthir [3] reported that fluoride stress induces various biochemical responses including increase in production of ROS that disrupt metabolism of plants that leads to LPO, denaturation of protein and damaged of DNA. Fluoride induced accumulation of ROS that are harmful present at high concentration in cell. ROS leads to oxidative damage in membrane proteins, lipids, nucleic acid and chlorophyll [52,53,54,55]. To scavenge these toxic species, plants employ antioxidants and detoxifying enzymes such as CAT, SOD and APX [23,56].

EFFECT OF SALT STRESS ON ANATOMY OF PLANT

Javid et al. [57] experimentally studied salt stress effect in leaves anatomy that shows small leaves size, stomatal frequency reduced and changed in mesophyll area. Salinity stress show adverse effect on cell division and cell expansion which decreased turgor pressure of cell expansion zone in the cells of growing leaves. Plants expose for prolonged salt stress cause shrinkage and complete distortion of chloroplast. It also been examined that salt stress cause plasmolysis and rupturing of plasmodesmata of leaf cells [41].

SI SUPPLEMENTATION IN SALT-STRESSED PLANTS CAUSE

Increase in Germination Rate

Salt stress inhibits germination of seed as soil restricts seeds to absorb water due to salt accumulate in soil [58]. Bybordi [59] studied Si increased the percentage of germination under salt-stressed condition in wheat plant. Haghighi et al. [60] proposed nano-silicon enhanced the rate of germination and germination percentage of tomato. Si enhanced the rate of germination, vitality index and germination index of *Momordica charantia* L., in salinity stress [61].

Restoration of Growth

Lee et al. [62] proposed that Si treatment enhance length of root and shoot, fresh and dry weight of plant, and chlorophyll content under salinity stress condition in soybean plants. Si improved growth of root and shoot biomass in purslane (*Portulaca oleracea* L.) plants under salinity stress [63]. Amirossadat et al. [64] studied Si treatment enhance height of plant, fresh and dry weight of plant and chlorophyll contents in cucumber plant under salinity stress. Salt stress significantly decreased length of shoot and root as compare to control in Mung bean plants. Conversely, addition of Si improves length of shoot and root under salt-stressed environment in Mung bean plants [18].

Increase in Yield

Si treatment enhances growth and biomass yield under high saline conditions in Mung bean plants [18]. Liang et al. [65] studied silicon increases quality and yield of various crops in agricultural, containing monocots like barley, millet, wheat, rice, sugarcane, maize, and sorghum, as well as dicots such as soybean and cotton. Si also enhance the rice yield growing in unstressed conditions by increasing photosynthesis, N-use efficiency and amino acids of vegetative tissues as well as grains [66,67]. Ali et al. [41] studied Si supplementation increased tillers number, grains per spike, and yield of grain under salt stress in wheat plants at field conditions]. Si application increased yield of pod, number of seeds per plant, yield of seeds and chlorophyll contents in *Vicia faba* L. under salt stress [68,69]. Parande et al. [70] studied Si treatment enhanced weight of seed and yield under salinity stress in bean plants (*Phaseolus vulgaris* L.).

Increase Photosynthetic Rate

Liang [22] experimentally studied that addition of Si increase the growth under salt stressed condition in barley plants via enhancing chlorophyll content and rate of photosynthetic in leaf cell organelles. Salinity stress cause decrease chlorophyll pigments concentration that decrease rate of photosynthetic and leads to poor plant growth [42]. In plants, addition of Si leads to enhance photosynthetic pigments in both normal and salt stress environment in Mung bean [71,18] and Maize [72]. Abbas et al. [73] examined that Si supplementation increase stomatal conductance, photosynthetic rate, rate of transpiration, and water use efficiency under salt stress in okra and tomato plants.

STIMULATION OF ANTIOXIDANTS BY ADDING SI UNDER SALT STRESS

Under stressful condition, plant defensive system become weak due to decrease antioxidants activity. Activities of both SOD and CAT activity decreased in salinity stress plant whereas LPO product (Malondialdehyde (MDA)) rapidly accumulates that leads to enhanced plasma membrane permeability. Plant defensive system enables them to improve salinity stress by the production of enzymatic and non-enzymatic antioxidants. Based on plenty of researches, defense system activity in plant affected by salt stressed can be improved through Si treatment [2]. Addition of Si decrease negative effect of salinity stress by enhancing CAT and SOD activity and soluble protein content in tomato leaves. Salinity stress slightly increase APX activity while Si treatment slightly decrease activity of APX as well as H_2O_2 and MDA concentration also decrease in leaves of tomato [74]. Si addition in cucumber plant under salt stress decrease Thiobarbituric acid reactive substances (TBARS), LPO and Hydrogen peroxide (H_2O_2) while increase APX, DHAR (dehydroascorbate reductase), SOD, GR (Glutathione reductase) and GPX (Guaiacol peroxidase) activities. Increase in

SOD, APX, GPX, GR and DHAR activities assist plants to withstand oxidative injury in salt stress condition, therefore reduce toxicity of salt and enhance cucumber plant growth [21].

Muneer and Jeong [75] experimentally studied that Si play significant role in detoxification of ROS through increasing antioxidant enzyme activities under salt stress in tomato plants. Addition of Si proved useful for plants in salinity stress condition through increase in GSH formation thus coupling directly with enzymatic components for quick ROS elimination and thus provides greater membrane protection. It has been studied that Silicon (Si) reduces MDA concentration, end- product of LPO in barley under salinity stress environment [76]. It also been reported to enhance antioxidant defense enzyme activity like CAT, SOD, GSH, POD and GR concentration under salt stress plants [21,74,76-80]. Zhu et al. [21] also demonstrated enhance in APX, POD, SOD, and GR activities through Si treatment under salt stressed cucumber.

CONCLUSION AND FUTURE PROSPECT

On the basis of plenty of attempts made in past, it is understandable that fluoride stress negatively affects the morphology, physiology and metabolism in crop plants. In this regard, Si can be used to decrease the harmful effect of fluoride on crop plants. Salinity tolerance shows complexity in traits and use of Si is worthwhile to mitigate this. In plants, to get salt tolerant crops through breeding though a successful but a herculean due to complexity and polygenic nature of salt tolerance traits. So, the detection of another feasible approach for improving salt tolerance in plants is very important. In that case, application of Si appears as an environmentally friendly implementation against salt stress in a cost-effective mode. Si application in fluoride and other salts affected soils is one of the easy and effective approaches which have great potential to mitigate the adverse effects of high salinity stress in important crop plants.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest in the course of conducting the research. All the authors had final decision regarding the manuscript and decision to submit the findings for publication.

REFERENCES

1. Rassol S, Ahmad A, Siddiqui TO, Ahmad P. Change in growth, lipid peroxidation and some key antioxidant enzymes in chickpea genotypes under salt stress. Acta Physiologiae Plantarum. 2013;35: 1039-1050.
2. Ali A, Basra SM, Hussain S, Iqbal J, Haji A, Sarwar M. Salt stress alleviation in field crops through nutritional supplementation of silicon. Pakistan Journal of Nutrition. 2012; 11(8):637-655.

3. Tak Y, Asthir B. Fluoride- induced changes in the antioxidant defence system in two contrasting cultivars of *Triticum aestivum* L. Research Report Fluoride. 2017;50(3):324-333.
4. Tylenda CA. Toxicological profile for fluoride, hydrogen fluoride and Fluorine (F). DIANE Publishing. 2011; 383.
5. Agalakova NI, Gusev GP. Fluoride induces oxidative stress and ATP depletion in the rat erythrocytes in vitro. Environment Toxicology and Pharmacology. 2012;34(2): 334-337.
6. Bhargava D, Bhardwaj N. Effect of Sodium Fluoride on Seed Germination and Seedling Growth of *Triticum aestivum* var. Rajasthan. 4083. Journal of Phytology. 2010;2(4):41-43.
7. Curnutte J, Babior B, Karnovsky M. Fluoride-mediated activation of the respiratory burst in human neutrophils: a reversible process. Journal of Clinical Investigation.1979;63:637-47.
8. Reddy MP, Kaur M. Sodium fluoride induced growth and metabolic changes in *Salicornia brachiata* Roxb. Water, Air, and Soil Pollution. 2008; 188:171-179.
9. Baunthiyal M, Ranghar S. Physiological and biochemical responses of plants under fluoride stress: An overview. Fluoride. 2014; 47(4):287-93.
10. Yadu B, Chandrakar V, Keshavkant S. Responses of plants to fluoride: An overview of oxidative stress and defense mechanisms. Research review Fluroide. 2016;49: 293-302.
11. Saini P, Khan S, Baunthiyal M, Sharma V. Effects of fluoride on germination, early growth and antioxidant enzyme activities of legume plant species *Prosopis juliflora.* Journal of Environmental Biology. 2013;34: 205-209.
12. Epstein E. Silicon. Annual review of plant physiology. 1999;50: 641–664.
13. Ma JF, Yamaji N. Silicon uptake and accumulation in higher plants. Trends in Plant Science. 2006;11: 392-397.
14. He C, Wang L, Liu J, Liu X, Li X, Ma J, Lin Y, Xu F. Evidence for ‘silicon’ within the cell walls of suspension-cultured rice cells. New Phytologist. 2013;200: 700–709.
15. Guerriero G, Hausman JF, Legay S. Silicon and the plant extracellular matrix. Frontiers in Plant Science. 2016;7: 463.
16. Liang YC, Chen Q, Liu Q, Zhang WH, Ding RX. Exogenous silicon increases antioxidant enzyme activity and reduces lipid peroxidation in roots of salt-stressed barley (*Hordeum vulgare* L.). Journal of Plant Physiology. 2003; 160:1157–1164.
17. Ma JF. Role of silicon in enhancing the resistance of plants to biotic and abiotic stresses. Journal of Soil Science and Plant Nutrition. 2004; 50:11-18.
18. Ahmad P, Ahanger MA, Alam P, Alyemeni MN, Wijaya L, Ali S, Ashraf M. Silicon (Si) supplementation alleviates NaCl toxicity in mung bean (*Vigna radiata* (L.) wilczek) through the modifications of physiobiochemical attributes and key antioxidant enzymes. Journal of Plant Growth Regulation. 2019;38: 70-82.
19. Romero-Aranda MR, Jurado O, Cuartero J. Silicon alleviates the deleterious salt effect on tomato plant growth by improving plant water status. Journal of Plant Physiology. 2006;163: 847-855.
20. Shu LZ, Liu YH. Effects of silicon on growth of maize seedlings under salt stress. Journal of Agro-environment Science. 2001; 20:38-40.

21. Zhu Z, Wei G, Li J, Qian Q, Yu J. Silicon alleviates salt stress and increases antioxidant enzymes activity in leaves of salt-stressed cucumber (*Cucumis sativus* L.). Plant Science. 2004;167: 527- 533.
22. Liang YC. Effects of Si on leaf ultrastructure, chlorophyll content and photosynthetic activity in barley under salt stress. Pedosphere. 1998;8: 289–296.
23. Liang YC. Effects of silicon on enzyme activity and sodium, potassium and calcium concentration in barley under salt stress. Plant and Soil. 1999;209: 217-224.
24. Rehman S, Harris PJC, Bourne WF, Wilkin J. The relationship between ions, vigour and salinity tolerance of Acacia seeds. Plant Soil. 2000;220: 229–233.
25. Khan MA, Weber DJ. Ecophysiology of high salinity tolerant plants. Tasks for vegetation science, 1st Edn. Springer, Amsterdam. 2008;40.
26. Lauchli A, Grattan SR. Plant growth and development under salinity stress. In: Jenks MA, Hasegawa PM, Mohan JS (eds) Advances in molecular breeding towards drought and salt tolerant crops. Springer, Berlin. 2007; 1–32.
27. Foolad MR, Lin GY. Genetic potential for salt tolerance during germination in *Lycopersicon* species. HortScience. 1997;32: 296–300.
28. Foolad MR, Lin GY. Genetic analysis of low temperature tolerance during germination in tomato, *Solanum lycopersicum* Mill. Plant Breeding. 1998;117: 171–176.
29. Lombardi T, Lupi B. Effect of salinity on the germination and growth of *Hordeum secalinum* Schreber (Poaceae) in relation to the seeds after-ripening time. Atti della societa toscana di scienze naturali, Memorie Serie B. 2006;113:37–42.
30. Khodarahmpour Z, Ifar M, Motamedi M. Effects of NaCl salinity on maize (*Zea mays* L.) at germination and early seedling stage. African Journal of Biotechnology. 2012;11: 298–304.
31. Sabal D, Khan TI, Saxena R. Effect of sodium fluoride on cluster bean (*Cyamopsis tetragonoloba*) seed germination and seedling growth. Research Report Fluoride. 2006; 39(3):228-230.
32. Chakrabarti S, Patra PK, Mandal B, Mahato D. Effect of Sodium fluoride on germination, seedling growth and biochemistry of Bengal gram (*Cicer arieninum*). Research Report Fluoride. 2012;45(3):257-262.
33. Garber PC. Fluoride uptake in plants. Fluoride – Quarterly Reports. 1968; 1(1):27-33.
34. Cooke JA. The uptake of sodium monofluoroacetate by plants and its physiological effects. Fluoride – Quarterly Report. 1976;9(4):204-212.
35. MacLean DC and Schneider RE. Effects of gaseous hydrogen fluoride on the yield of field-grown wheat. Environmental Pollution. 1981; 24:39-44.
36. Tuna MA, Persaud N and Baligar VC. Effect of fluoride and phosphate on yield and mineral composition of barley grown on three soils. Communication in Soil Science and Plant Analysis. 1998; 29:269-283.
37. Stevens DP, McLaughlin MJ, Alston AM. Phytotoxicity of the fluoride ion and its uptake from solution culture by *Avena sativa* and *Lycopersicon esculentum.* Plant and Soil. 1998a; 200:119-129.

38. Stevens DP, McLaughlin MJ, Alston AM. Phytotoxicity of hydrogen fluoride and fluoroborate and their uptake from solution culture by *Avena sativa* and *Lycopersicon esculentum.* Plant and Soil. 1998b;200: 175-184.
39. Datta JK, Maitra A, Mondal NK, Banerjee A. Studies on the impact of fluoride toxicity on germination and seedling growth of gram seed (*Cicer arietinum* L. cv. Anuradha). Journal of Stress Physiology & Biochemistry. 2012;8(1):194-202.
40. Gadi BR, Verma P, Amra R. Influence of NaF on seed germination, membrane stability and some Biochemicals content in *Vigna* seedlings. Journal of Chemical, Biological and Physical Sciences. 2012;2(3):1371-1378.
41. Ali A, Basra SM, Iqbal J, Hussain S, Subhani MN, Sarwar M, Haji A. Silicon mediated biochemical changes in wheat under salinized and non-salinized solution cultures. African Journal of Biotechnology. 2012;11: 606– 615.
42. Tuna AL, Kaya C, Ashraf M, Altunlu H, Yokas I, Yagmur B. The effects of calcium sulphate on growth, membrane stability and nutrient uptake of tomato plants grown under salt stress. Environmental and Experimental Botany. 2007;59: 173–178.
43. Baunthiyal M, Bhatt A, Ranghar S. Fluoride and its effects on plant metabolism. Journal of Agricultural Science and Technology. 2014;10(1): 1-27.
44. Kumar KA, Rao AVB. Physiological responses to fluoride in two cultivars of Mulberry. World Journal of Agricultural Science. 2008;4(4):463-466.
45. Saleh AH, Abdel-Kader Z. Metabolic responses of two *Helianthus annus* cultivars to different fluoride concentrations during germination and seedling growth stages. Egyptian Journal of Biology. 2003;5: 43-54.
46. Shi H, Wang X, Ye T, Chen F, Deng J, Yang P, Zhang Y, Chan Z. The Cysteine2/Histidine2-type transcription factor zinc finger of *Arabidopsis thaliana* 6 modulates biotic and abiotic stress responses by activating salicylic acid-related genes and C-REPEAT-BINDING FACTOR genes in *Arabidopsis*. Plant Physiology. 2014; 165:1367–1379.
47. Ahanger MA, Agarwal RM. Salinity stress induced alterations in antioxidant metabolism and nitrogen assimilation in wheat (*Triticum aestivum* L) as influenced by potassium supplementation. Plant Physiology and Biochemistry. 2017; 115:449–460.
48. Ahmad P, Hashem A, Abd-Allah EF, Alqarawi AA, John R, Egam- berdieva D, Gucel S. Role of *Trichoderma harzianum* in mitigating NaCl stress in Indian mustard (*Brassica juncea* L) through antioxidative defense system. Frontiers in Plant Science. 2015; 6:868.
49. Manai J, Kalai T, Gouia H, Corpas FJ. Exogenous nitric oxide (NO) ameliorates salinity-induced oxidative stress in tomato (*Solanum lycopersicum*) plants. Journal of Soil Science and Plant Nutrition. 2014; 14(2).
50. Ahmad P, Ozturk M, Sharma S, Gucel S. Effect of sodium carbonate-induced salinity–alkalinity on some key osmoprotectants, protein profile, antioxidant enzymes, and lipid peroxidation in two mulberry (*Morus*

alba L.) cultivars. Journal of Plant Interaction. 2013;9: 460–467.

51. Ahmad P, Abdel Latef AA, Hashem A, Abd_Allah EF, Gucel S, Tran L-SP. Nitric oxide mitigates salt stress by regulating levels of osmolytes and antioxidant enzymes in chickpea. Frontiers in Plant Science. 2016; 7:347.
52. Mittler R. Oxidative stress, antioxidants and stress tolerance. Trends in Plant Science. 2002;7: 405-410.
53. Karabal E, Yucel M, Oktem H. Antioxidant responses of tolerant and sensitive barley cultivars to boron toxicity. Plant Sciences. 2003;164: 925-933.
54. Keles Y, Once I, Yenice N. Relationship between boron content and anti- oxidant compounds in citrus leaves taken from field with different water sources. Plant and Soil. 2004; 265:345-353.
55. Gunes A, Inal A, Bagci EG. Silicon-mediated changes of some physiological and enzymatic parameters symptomatic for oxidative stress in spinach and tomato grown in sodic-B toxic soil. Plant and Soil. 2007; 290:103-114.
56. Molassiotis A, Tanou G, Diamantidis G, Therios I.Boron-induced oxidative damage and antioxidant and nucleolytic responses in shoot tips culture of apple rootstock EM9 (*Malus domestica*). Environmental and Experimental Botany. 2006; 56:54-62.
57. Javid I H, Wahid A, Rasul E. Some growth and anatomical studies in the leaf and root of differently salt tolerant pearl millet lines under salinity. Journal of Plant Physiology. 2000; 10:185-190.
58. Gupta B, Huang B. Mechanism of salinity tolerance in plants: physiological, biochemical, and molecular characterization. International Journal of Genomics. 2014.
59. Bybordi A. Interactive effects of silicon and potassium nitrate in improving salt tolerance of wheat. Journal of Integrative Agriculture. 2014; 13:1889–1899.
60. Haghighi M, Afifipour Z, Mozafarian M. The effect of N–Si on tomato seed germination under salinity levels. Journal of Biological and Environmental Sciences. 2012;6(16): 87–90.
61. Wang XD, Ou-yang C, Fan ZR, Gao S, Chen F, Tang L. Effects of exogenous silicon on seed germination and antioxidant enzyme activities of *Momordica charantia* under salt stress. J Anim Plant Sci. 2010;6(3):700–708.
62. Lee SK, Sohn EY, Hamayun M, Yoon JY, Lee IJ. Effect of silicon on growth and salinity stress of soybean plant grown under hydroponic system. Agroforestry Systems. 2010;80: 333–340.
63. Kafi M, Rahimi Z. Effect of salinity and silicon on root characteristics, growth, water status, proline content and ion accumulation of purslane (*Portulaca oleracea* L.). Soil science and Plant Nutrition. 2011;57: 341-347.
64. Amirossadat Z, Ghehsareh AM, Mojiri A. Impact of silicon on decreasing of salinity stress in greenhouse cucumber (*Cucumis sativus* L.) in soilless culture. Journal of Biological and Environmental Sciences. 2012; 6:171-174.
65. Liang Y, Nikolic M, Belanger R, Gong H, Song A. Effect of silicon on crop

growth, yield and quality. Silicon in Agriculture. 2015;209-223.

66. Detmann KC, Araujo WL, Martins SCV, Sanglard LM, Reis JV, Detmann E, Rodrigues FA, Nunes-Nesi A, Fernie AR, Damatta FM. Silicon nutrition increases grain yield, which, in turn, exerts a feed- forward stimulation of photosynthetic rates via enhanced mesophyll conductance and alters primary metabolism in rice. New Phytologist. 2012;196: 752-762.
67. Detmann KC, Araujo WL, Martins SCV, Fernie AR, Damatta F. Metabolic alternations triggered by silicon nutrition: Is there a signaling role for silicon? Plant Signaling and Behavior. 2013;8(1): e22523.
68. Hellal FA, Abdelhameid M, Abo-Basha DM, Zewainy RM. Alleviation of the adverse effects of soil salinity stress by foliar application of silicon on faba bean (*Vicia faba* L.). Journal of Applied Science Research. 2012;8(8): 4428–4433.
69. Kardoni F, Mosavi SJS, Parande S, Torbaghan ME. Effect of salinity stress and silicon application on yield and component yield of faba bean (*Vicia faba*). International Journal of Agriculture and Crop Sciences. 2013; 6:814–818.
70. Parande S, Zamani GR, Zahan MHS, Ghader M. Effects of silicon application on the yield and component of yield in the common bean (*Phaseolus vulgaris*) under salinity stress. International Journal of Agronomy and Plant Production. 2013;4: 1574–1579.
71. Mahmood S, Daur I, Al-Solaimani SG, Ahmad S, Madkour MH, Yasir M, Hirt H, Ali S, Ali Z. Plant growth promoting rhizobacteria and silicon synergistically enhance salinity tolerance of mung bean. Frontiers in Plant Science. 2016;7: 876.
72. Parveen N, Ashraf M. Role of silicon in mitigating the adverse effects of salt stress on growth and photosynthetic attributes of two maize (*Zea mays* L.) cultivars grown hydroponically. Pakistan Journal of Botany. 2010;42: 1675–1684.
73. Abbas T, Balal RM, Shahid MA, Pervez MA, Ayyub CM, Aqueel MA, Javaid MM. Silicon-induced alleviation of NaCl toxicity in okra (*Abelmoschus esculentus*) is associated with enhanced photosynthesis, osmoprotectants and antioxidant metabolism. Acta Physiologiae Plantarum. 2015;37: 6.
74. Aghabary K, Zhu Z, Shi QH. Influence of silicon supply on chlorophyll content, chlorophyll fluorescence, and antioxidative enzyme activities in tomato plants under salt stress. Journal of Plant Nutrition. 2004;27: 2101–2115.
75. Muneer S, Jeong BR. Proteomic analysis of salt-stress responsive proteins in roots of tomato (*Solanum lycopersicum* L.) plants towards silicon efficiency. Plant Growth Regulation. 2015;77: 133-146.
76. Liang YC, Chen Q, Liu Q, Zhang W, Ding R. Effects of silicon on salinity tolerance of two barley cultivars. Journal of Plant Physiology. 2003; 160:1157- 1164.
77. Liang Y, Zhang W, Chen Q, Liu Y, Ding R. Effect of exogenous silicon (Si) on H+-ATPase activity, phospholipids and fluidity of plasma membrane in leaves of salt-stressed barley (*Hordeum vulgare* L.). Environmental and Experimental Botany. 2006;57 :212–219.
78. Shi Y, Zhang Y, Han W, Feng R, Hu Y, Guo J, Gong H. Silicon enhances

water stress tolerance by improving root hydraulic conductance in *Solanum lycopersicum* L. Frontiers in Plant Science. 2016;7: 196.

79. Zhu YX, Gong HJ, Yin JL. Role of silicon in mediating salt tolerance in plants: A review. Plants (Basel). 2019;8(6):147.
DOI: 10.3390/plants8060147

80. Khan A, Khan AL, Muneer S, Kim Y-H, Al-Rawahi A and Al-Harrasi A. Silicon and salinity: Crosstalk in crop-mediated stress tolerance mechanisms. Front. Plant Sci. 2019; 10:1429.
DOI: 10.3389/fpls.2019.01429.
