Exogenous use of sodium nitroprusside and silicon to alleviate detrimental NaCl impact in *Solanum lycopersicum* (cv. Isabella) during vegetative stage

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Abstract

One of the most deleterious abiotic stresses is the salinity stress, which causes inhibition of growth and development. Therefore, this investigation was conducted with aim of evaluating the effects of sodium nitroprusside (SNP) and silicic acid (Si) on biochemical response of *Solanum lycopersicum* (cv. Isabella) under different levels of salinity during vegetative stage. For this purpose, the seedlings were subjected to the different levels of salt stress (0, 25, 50, 100, and 150 mM) and supplemented with optimized concentration of silicon (Si) (0, 2.5 mM) and sodium nitroprusside (SNP) (0, 100 µM) to assess variations in enzymatic and biochemical properties of tomato plant during vegetative growth. Salt stress inhibited the chlorophyll and carotenoid contents of tomato plants. The antioxidant enzyme activities such as catalase (CAT) and superoxide dismutase (SOD) as well as the levels of osmolytes (proline, glycine betaine), malondialdehyde (MDA), and hydrogen peroxide (H₂O₂) increased in tomato plants due to high salinity. Furthermore, the exogenous use of SNP and Si for salinizing the plants increased the antioxidant enzyme activities and osmolyte levels compared to NaCl-treated plants. In addition, in the plants under salt stress, which were supplemented with SNP and Si, the contents of MDA and H₂O₂ decreased compared to the plants treated with NaCl alone. Therefore, the exogenous use of Si and SNP led to protecting tomato plants against oxidative damage induced by salt stress by stimulating synthesis of antioxidant enzyme. Finally, under saline stress, plant growth improved. The findings indicated that with the improvement in antioxidative defense system, pigment syntheses, and osmolyte accumulation, SNP and Si had the ability to alleviate adverse impact of high salinity on tomato plant.

Keywords: Antioxidant enzyme, Chlorophyll content, Salinity, Tomato

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Introduction

One of the most deleterious abiotic stresses is defined as salinity stress, which causes the inhibition of development, growth (Roy and Mishra, 2014) as well as a decrease in respiration, protein synthesis, and photosynthesis (Karimi et al., 2005), osmotic stress, production of reactive oxygen species (ROS), and ion toxicity (Mittler, 2002; Wu et al., 2010). ROS such as peroxide hydrogen (H_2O_2) is too reactive to damage the lipids, protein and nucleic acid (Foyer and Noctor, 2000). ROS production is scavenged by a variety of types of antioxidant enzymes such as catalase (CAT), glutathione reductase (GR), guaiacol peroxidase (POD), ascorbate peroxidase (APX), superoxide dismutase (SOD), and antioxidant compounds (Foyer and Noctor, 2003). Therefore, the antioxidant system should be elevated in plant organs to enhance salt stress tolerance and mitigate such stress (Wu et al., 2010) or with exogenous application of some compounds which are capable of alleviating salinity stress.

The second most abundant substrate in soil is silicon (Si), which can alleviate stresses such as drought, heat, chilling, and salt (Liang et al., 2007; Wang et al., 2010). Some studies have demonstrated that silicon is essential element in the growth and development of plants (Epstein, 1994; Kim et al., 2014). Additionally, several studies have reported the beneficial effect of this element to mitigate the salt stress in different plant species such as barley (Liang et al., 2003), cucumber (Zhu et al., 2004), soybean (Lee et al., 2010), sugarcane (Ashraf et al., 2010), cherry tomato (Haghighi and Pessarakli, 2013), and squash (Siddiqui et al., 2014). Numerous studies have suggested that the exogenous application of silicon can ameliorate the production of ROS by regulation of antioxidant enzyme activity (Kim et al., 2017; Tripathi et al., 2017). Torabi et al. (2015) demonstrated that the exogenous application of Si can promote a decrease in CAT and an increase in SOD in borage plant.

Nitric oxide (NO), a reactive nitrogen species, is an abundant bioactive molecule and a small, highly diffusible, gaseous-free radical (Lamattina et al., 2003). It has a major role as a signaling molecule and also showed various biological functions in plants (Wu et al., 2010). NO have a protective impact as a response to biotic and abiotic stresses. In relation to

abiotic stresses, application of sodium nitroprusside has been suggested to reduce the adverse impacts of salinity on plants (Fan et al., 2012). The use of the NO treatment in plant species resulted in different responses to salinity stress (Begara-Morales et al., 2014). Fan et al. (2012) found that the exogenous use of NO ameliorated salinity damage in cucumber seedlings by reducing the adverse impacts of salinity stress and regulating proline metabolism.

Tomato plant is one of important greenhouse crops throughout the world. High salinity in soil heavily influences its growth. Tomato plant shows different responses to salinity stress depending on cultivar and growth stage (Roy and Mishra, 2014). However, information on the interaction of salinity, Si and NO applications on tomato seedling growth and performances are still scarce. Therefore, the objective of the present research was to evaluate effect of sodium nitroprusside and silicic acid on biochemical response of tomato (*Solanum lycopersicum* cv. Isabella) under different levels of salinity during vegetative stage.

Material and Methods

Plant material and growth conditions

In a greenhouse at Jahrom Azad Agricultural University, Fars, Iran, the experiment was conducted. *Solanum lycopersicum* (cv. Isabella, F₁ Hybrid) seeds were purchased from Monsanto company. In plastic pots that contain five kg of a sterilized potting mix (sand, clay and leaf mold, 1:1:2), the seeds were planted in a greenhouse where the mean temperature per day/night and relative humidity were 30/20±2°C and 50%, respectively. Table 1 shows some of the physicochemical characteristics of the media.

The seedlings were irrigated with tap water until commencement of salt treatment. When seedlings reached four to six leaf stage, salinity treatments were executed. Sodium chloride solutions containing 0 (distilled water only as control treatment), 25, 50, 100, and 150mM were applied with irrigation for 40 days duration until flowering stage (from 3 April to 13 May, 2018). Before beginning salt treatments, pots were irrigated with tap water to field capacity. Sodium chloride (Merck, Darmstadt, Germany) was dissolved in tap water to achieve the desired conductivity.

Table-1: Some of physicochemical characteristics of potting soil

SO ⁻² ₄	HCO ⁻² ₃	CO ⁻² ₃	Ca	Cl	Mg	K	Na	E.C (µs/cm)	pH	S.A.R*
(meq/l)										
40	-	5.5	37.5	7.5	5.5	0.45	12.52	3840	7.92	2.7

*Sodium adsorption ratio

The treatments were applied incrementally, increasing by 25 mM every 1 week, over a 5 week period, to achieve the highest level of salinity in order that an osmotic shock to the plants could be avoided. For each irrigation, the soil moisture content was increased to field capacity level by weighing the pots. To prevent the salt accumulation in the pots, when the EC of pot outlet solution was 1.5 times the EC of the initial solution, the leaching was carried out. At the same time with salinity stress, leaves were sprayed with silicic acid (Si donor) at zero and 2.5mM and SNP (NO donor) at zero and 100µM. After 5 weeks the leaf samples were harvested for each analysis.

Measurements and observations of leaf sample

Proline content

Using 3% sulfosalicylic acid, 0.2 g of leaf sample was homogenized. Then, acid-ninhydrin was added and the content of proline was measured with the use of the method employed by Batse et al. (1973). A spectrophotometer (UV-120-20, Japan) was utilized to measure the absorbance of the fraction with toluene at 520nm.

Glycine Betaine determination

Using 20ml of deionized water, 0.5g of leaf sample was homogenized. Then, leaf samples were shaken for 48 hours at a temperature of 25°C. Using 2N H₂SO₄, the extracts were diluted 1:1. Aliquots were allowed to be cooled down by ice water for one hour. The cold KI-I₂ reagent (0.20ml) was added using a vortex mixer, the reactants were gradually stirred. The tubes were kept at a temperature of 4°C for 16 h and then centrifuged at 10,000rpm at 0°C for 15 minutes. The solubility of the complexes in a reaction mixture of acid considerably increases with temperature. Therefore, tubes were kept cold until the complex of periodide is separated from the acid media. The crystals of periodide were dissolved in 9 ml of 1,2-dichloroethane. After two hours, with the use of a spectrometer (Shimadzu UV-1700), the absorbance was determined at 365 nm (Grieve and Grattan, 1983).

Total phenolic content

The Folin-Ciocalteu reagent used by Velioglu et al. (1998) was utilized with some modifications to determine the total phenolic content. Two hundred (200) mg of the sample was extracted with 2 ml of 80% methanol using an orbital shaker at 200 rpm at room temperature for 2 hours. The mixture was centrifuged at 1000 rpm for 15 minutes and the pellet was used as extract. One hundred (100) µl of the extract and 1.5ml of Folin-Ciocalteu reagent (previously diluted 10-fold with the distilled water) were mixed and kept at a temperature of 22°C for 5 minutes. Then, 1.5ml of 20% sodium bicarbonate solution was added to the mixture. After 90 minutes, the absorbance was determined at 750nm.

Lipid peroxidation (Malon Dialdehyde)

The thiobarbituric acid reaction according to the method employed by Heath and Packer (1968) with some modification was utilized to measure the level of lipid peroxidation in the tissue of leaves. Half gram leaf sample was homogenized with 10 ml of 0.1% trichloroacetic acid (TCA). The homogenate was centrifuged at 1500 rpm for 15 minutes. Four (4) ml of 20% TCA that contained 0.5% TBA were added to 1 ml supernatant aliquot. The mixture was heated at 95°C for 30 minutes and kept in an ice bath. Then, the mixture was centrifuged at 10000 rpm for 10 minutes, and the supernatant absorbance was measured at 532nm and 600nm. After subtracting the two wavelengths, concentration of MDA was determined with the use of the extinction coefficient of 15mM cm⁻¹ (Heath and Packer, 1968).

Peroxide Hydrogen assay

The content of hydrogen peroxide (H₂O₂) of the leaves was assayed based on the method used by Velikova et al. (2000). The leaves were homogenized with 0.1% (w/v) TCA in an ice bath. The extract was centrifuged at 12,000 rpm for 15 minutes, and the supernatant was added to 0.5 ml of 1 M KI and 0.5ml of 10mM potassium phosphate buffer at a pH 7, and the absorbance was read at 390nm using Shimadzu UV-1700 spectrophotometer.

Activity of enzymes

Catalase assay

Half gram leaf tissue, was homogenized with 5 ml of 50mM phosphate buffer that contained 1% insoluble polyvinylpyrrolidone at pH =7. The homogenate was centrifuged at 15000 rpm for 10 minutes and the obtained supernatant was utilized as the enzyme extract. The initial rate of disappearance of hydrogen peroxide was measured according to the method employed by Maehly and Chance (1954) to assay the catalase enzyme. One ml of reaction mixture contained 25 μ l of enzyme extract, 15 mM of hydrogen peroxide and 50mM of phosphate buffer at pH =7. The reduction in hydrogen peroxide was followed as a decrease in A_{240} with a spectrophotometer (Shimadzu UV-1700). One unit of the catalase activity was defined as the value of 0.01 at 240nm after incubation for one minute.

Superoxide Dismutase assay

Fresh sample (0.25 g) was ground to a fine powder in liquid N₂ and then homogenized with 1% PVPP, 2mM NaEDTA, and 1ml of 50mM phosphate potassium buffer; at a pH =7. The homogenate was centrifuged twice and the supernatants were used for the spectrophotometric assays to measure the SOD. The SOD ability to prevent the photochemical reduction in nitroblue tetrazolium (NBT) at 560nm, based on the method employed by Dhindsa et al. (1981) was measured spectrophotometrically to estimate SOD activity. The enzymatic activity was expressed as U g⁻¹ FW.

Chlorophyll and carotenoid

Carotenoid and chlorophyll were determined based on the method employed by Arnon (1949). The content of chlorophyll was spectrophotometrically measured at 480 nm for carotenoid and at 645nm and 663nm for chlorophyll. Concentrations of carotenoid and chlorophyll were determined by the equations used by Arnon (1949).

$$\text{Chl. } a = 0.0127 A_{663} - 0.00269 A_{645}$$

$$\text{Chl. } b = 0.00229 A_{645} - 0.00468 A_{663}$$

$$\text{Carotenoid} = (1000A_{470} - 1.8\text{chl.a} - 85.2\text{chl.b})/198$$

Statistical analysis

The experiment was carried out based on a completely randomized design (CRD) as factorial arrangement with five replications (one seedling in each replication). The SAS software (Ver. 9.4) was used to

analyze the data and LSD was utilized to compare significant differences between the mean data at $P \leq 0.05$.

Results

The data analysis of variance (results not displayed) indicated that there was significant interaction between the factors. On this basis, the mean comparison of the interaction between factors has been explained.

Proline

The results (Fig. 1) showed that as salinity increased, proline content significantly increased without application of Si and SNP. Under higher levels of salinity, proline content increased with application of 2.5 mM Si (0.0743, 0.0644 $\mu\text{g g}^{-1}$ of F.W.).

Figure-1- Impact of Si and SNP on proline content under different salinity levels.

The columns having same letters are not different according to LSD test ($P \leq 0.05$).

MDA concentration, Glycine betaine, H₂O₂

The addition of Si dramatically reduced MDA content in leaf under salinity stress (Fig. 2A). The addition of NaCl in the presence of SNP and Si slightly increased MDA content in leaves of tomato plants stressed with 150 mM NaCl, in which lowest MDA content was observed in Si + SNP in 150mM NaCl. As salinity increased, glycine betaine content increased without application of Si and SNP. Glycine betaine reached highest level in 150 mM NaCl with application of SNP + Si. The minimum content of glycine betaine was observed in control (no salt stress) but it had no significant difference with the most treatments, so that it had significant difference only with the treatments including Si_{2.5}+SNP₁₀₀ in NaCl 50 as well as in NaCl

100, in addition with Si₀+SNP₀ in NaCl 150 (Fig. 2B). Salt stress at 150 mM enhanced the H₂O₂ content, however, added Si and SNP reduced the content of H₂O₂ under the highest level of salt stress (150 mM NaCl) (Fig. 2C).

Figure 2- Impact of Si and SNP on MDA (A), Glycine betaine (B) and H₂O₂ (C) content under different salinity levels.

The columns having same letters are not different according to LSD test ($P \leq 0.05$).

Total phenolic content

Total phenolic content significantly increased as salinity increased, however, with application of Si and SNP, phenol content decreased (Fig. 3). The maximum and minimum content of phenol was observed in no application of Si and SNP under 150 mM NaCl and Si_{2.5}+SNP₁₀₀ without salt stress, respectively (Fig. 3).

Figure-3: Impact of Si and SNP on total phenol content under different salinity levels.

The columns having same letters are not different according to LSD test ($P \leq 0.05$).

Enzyme activities

As the result indicated in Fig. 4A, CAT activity increased in application of 100 μM SNP under salinity of 150 mM NaCl and decreased with Si in plants treated with 25 mM NaCl, whilst, the activity of SOD enhanced with foliar application of Si in 150 mM NaCl. SOD decreased with application of SNP in plants stressed with 25 mM NaCl (Fig. 4B).

Figure-4: Impact of Si and SNP on on catalase (A) and SOD (B) enzymes activity under different salinity levels.

The columns having same letters are not different according to LSD test ($P \leq 0.05$).

Chlorophyll and carotenoid content

Amounts of chlorophyll *a*, chlorophyll *b* and carotenoid dramatically decreased under conditions of salinity stress. However, the addition of Si and SNP raised amounts of chlorophyll *a*, chlorophyll *b* and carotenoid under conditions of salinity stress. Amounts of chlorophyll *a*, chlorophyll *b* and carotenoid decreased in the highest level of salinity, but Si at 2.5 mM improved amounts of chlorophyll *a* and chlorophyll *b* at 150 mM NaCl. SNP at 100 μM enhanced carotenoid content in plants treated at 150 mM NaCl (Fig. 5).

Figure 5- Impact of Si and SNP on on chlorophyll a (A), chlorophyll b (B) and carotenoid (C) content under different salinity levels.

The columns having same letters are not different according to LSD test ($P \leq 0.05$).

Discussion

Salinity stress has been shown to dramatically change the biochemical responses of Isabella tomato cultivar. Exogenous application of silicic acid and sodium nitroprusside decreased the effect of salinity stress, thereby improving biochemical responses of the plant. The findings indicated that SNP and Si improved proline content under salinity condition (Fig. 1). Similarly, the impact of SNP and Si have been documented in relation to tomato plant (Manai et al., 2014) and a cucumber seedling (Siddiqui et al., 2014), respectively. Plants produce several different compatible solutes such as total phenolic content, glycine betaine, and proline under conditions of stress. The results of our research demonstrated that Si and SNP increased the proline and glycine betaine content (Fig. 1, 2B). The current result of this study is in line with earlier studies (Fan et al., 2012; Abbas et al., 2015;), where an increase in proline and glycine betaine was indicative of an osmotic adjustment capacity of plants under conditions of salt stress. In another study on pepper cultivar, improving potential for an osmotic adjustment in terms of increasing compatible solutes by Si resulted in high photosynthetic activities and considerable growth under conditions of salt stress (Fan et al., 2012). Generally, it can be presumed that Si can alleviate the damaging impacts of salinity stress by an increase in the accumulation of organic osmolytes that reduced an osmotic shock induced by NaCl stress owing to ion toxicity.

Nevertheless, some studies described that Si and SNP enhanced total phenolic content (Jamali et al., 2014; Abbas et al., 2015). Our research demonstrated that the SNP and Si treatments had lower total phenolic content than non-SNP and Si treated plant (Fig. 3). It seemed that reduction of this osmolyte by application of Si and SNP on tomato leaf was probably depended on genotype, cultivar and severity of salinity stress. Therefore, more detailed study is needed to investigate such differences in findings.

The present study suggested that Si and SNP treatments reached highest CAT and SOD activity during salinity condition (Fig. 3A, B). The findings supported the results of previous studies done on distinct plant species, in which CAT and SOD activities increased by the use of SNP and Si under conditions of salt stress (Kim et al., 2014; Siddiqui et al., 2014; Jamali et al., 2014). Due to high ROS production under conditions of salt stress, plants induce an antioxidant mechanism to prevent damage to cellular components and increase tolerance to salinity by the ROS scavenging system (Alscher et al., 2002). Additionally, foliar applied-Si intensified the ROS scavenging under saline condition. Tripathi et al. (2013) and Farooq et al. (2013) found that Si is a possible substrate to regulate various activities of antioxidant enzymes. The simultaneous use of NaCl and sodium nitroprusside raised the CAT and SOD activities in a tomato plant (Fig. 3A, B). This finding is in line with the results of other studies done on mustard (Khan et al., 2012), tomato (Manai et al., 2014) chick pea (Ashraf et al., 2010) plants. Nitric oxide (NO) can play an important role in ROS scavenging and antioxidant system stimulation to increase the expression of the genes that encode antioxidant enzymes- (Grob et al., 2013). Furthermore, the exogenous NO use might induce the synthesis of endogenous NO to act as signaling molecule in above-mentioned cascades (Zhao et al., 2009). Consequently, it is possible that SNP and Si eliminated ROS by elevating the antioxidant activities and thus mitigated toxicity induced by NaCl in a tomato plant depending on severity of salinity.

In our study, Si considerably ameliorated the drastic impact of lipid peroxidation on the membrane under salinity condition by reducing the content of the MDA in tomato plants (Fig. 2A). Si has also been reported to stabilize cell membrane integrity and sustaining their permeability under conditions of abiotic stress (Jiao-Jing et al., 2009).

The leaves of tomato plants under salinity stress accumulated a high level of H_2O_2 content (Fig. 2C), which cause oxidative damage. The exogenous use of SNP and Si decreased H_2O_2 in NaCl-treated tomato, which is not in accordance with the observation of Zhu et al. (2004) and Khan et al. (2012). Consequently, using SNP and Si might lead to protecting plants against oxidative damage induced by salinity stress. Some studies also suggested that SNP and Si possess the ability to defend cell membranes by alleviating damage to the cell membrane system and lowering the permeability of membranes.

The reduction in chlorophyll *a* and chlorophyll *b* in the leaves of tomato plants observed under stress condition (Fig. 5A, B) might be recognized as the destruction of chlorophyll pigments that resulted in reducing chlorophyll syntheses (Rasool et al., 2013). It has been shown that the synthesis of carotenoids lead to decreasing them in the leaves of tomato plants under NaCl stress. However, SNP and Si (Fig. 5C) have been shown to stimulate improvement in the photosynthetic pigments in tomato plant, because these compounds have a major role in mitigating oxidative damage caused by NaCl stress. This study is in accordance with previous research on tomato (Wu et al., 2010) and rice (Habib et al., 2013) plants.

Conclusion

Stress induced by NaCl led to a decrease in malondialdehyde (MDA), hydrogen peroxide (H_2O_2) and green pigments, and thereby resulting in decrease in catalase (CAT) and superoxide dismutase (SOD) activities and accumulation of osmolytes (glycine betaine and proline). Improvement in growth owing to spraying with sodium nitroprusside and silicon is caused by an increase in the antioxidant activities and of certain osmolyte levels. This resulted in elevating carotenoids and total chlorophyll content under NaCl stress. Consequently, it is recommended that sodium nitroprusside (SNP) and Si are effective agents for mitigating stress in order that tomato plants can be protected against toxicity induced by NaCl. Therefore, the exogenous use of silicic acid (Si) and SNP led to protecting a tomato plants against oxidative damage induced by salt stress and by stimulating synthesis of antioxidant enzyme. Finally, under saline stress, plant growth improved. The findings indicated that with the improvement in antioxidative defense system, pigment syntheses, and osmolyte accumulation, SNP and Si had the ability to alleviate adverse impact of

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Contribution of Authors

Ghanaatian N: Conceptualized part of the research, performed the experiment, data collection and collation, carried out data analysis and wrote the manuscript.

Jahromi AA, Sadeghi H, Jari SK & Behrooznam B: Conceptualized the research, supervised the work and edited and finally approved the manuscript.