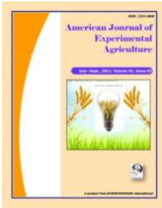

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Influence of Silicon and Nano-Silicon on Germination, Growth and Yield of Faba Bean (*Vicia faba* L.) Under Salt Stress Conditions

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

Aims: The present study was conducted to evaluate the effects of Silicon (Si) and Nano-Silicon (NSi) for ameliorating negative effects of salinity on germination, growth and yield of faba bean (*Vicia faba* L.).
Study Design: Factorial completely randomized design Pot experiments used with Si and NSi applied at 4 concentrations each (0, 1, 2 and 3 mM) and NaCl (0, 50, 100 and 200 mM) were studied.
Place and Duration of Study: Experiments were carried out in the greenhouse of Faculty of Science, Princess Nora Bint Abdulrahman University, Kingdom of Saudi Arabia during winter season of 2010/2011
Methodology: Si and NSi applied at 4 concentrations each (0, 1, 2 and 3 mM) and NaCl (0, 50, 100 and 200 mM) were studied. Germination characteristics such as germination percentage (GP), germination rate (GR) and mean germination time (MGT) were measured. Vegetative growth including plant height, leaf area and fresh and dry weights was also studied. Yield and its components were determined. Nutrient elements (N, P, K, Ca and Na) in the seeds were also determined.

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Results: Results showed that salinity had deleterious effects on seed germination, plant growth and yield. N, P, Ca and K in seeds decreased at salinity stress but Na increased. Application of Si and NSiO2 significantly enhanced the characteristics of seed germination. Among the treatments, 2mM of Si or NSiO2 improved GP, GR and MGT. The harmful effect of salt stress on vegetative growth and relative water content (RWC) was also alleviated by the addition of Si and NSi which caused significant increases in plant height, fresh and dry weights, RWC and total yield. Seed quality, represented by nutrient elements, was also improved by application of Si and NSi.

Conclusion: It is concluded that the application of Si was beneficial in improving the salt tolerance of *Vicia faba* plants.

Keywords: Silicon; nanosilicon; faba bean; germination; growth; yield.

1. INTRODUCTION

Salinity is a major stress condition at present [1] and is one of the most serious environmental problems influencing crop growth [2] and together with drought continues to be one of the world's most serious environmental problems in agriculture. This problem is particularly serious in arid and semi-arid regions of the world [3]. Salinity causes not only differences between the mean yield and the potential yield, but also causes yield reduction from year to year. It affects seed germination and plant growth directly through its interaction with metabolic rates and pathways within the plants [3]. Among nutrient elements, silicon (Si) is regarded as one of the most beneficial elements for the plant life [4]. The ability of Si to ameliorate the negative effect of salt stress on plant growth is well documented [5]. Several investigators have reported that silicon enhanced salt tolerance of many crop species [6] and [7]. It was found that Si application improved growth and yield through improving plant water status, changes in ultra-structure of leaf organelles, activation of plant defense systems and mitigation of specific ions [8].

Nano-particles have become a centre of attraction for researchers because of its unique physico-chemical properties compared to their bulk particles [9]. Recently, nano-compound materials have given a lot of attention by the agricultural researchers [10] and [11]. Because of their tiny size, nano materials show unique characteristics. For example, they can change physico-chemical properties compared to bulk materials. They have greater surface area than bulk materials, and due to this larger surface area, their solubility and surface reactivity tend to be higher [12]. Nano-silicon (NSi) is one of the useful nano materials which are reported to have a beneficial effect in modern agriculture [13]. However, understanding the mode of action of nanoparticles on plant growth and development is still insufficient. Bao-shan et al. [14] observed that nano-silica (NSi) improved growth and quality of *Larix* seedlings. NSi showed the highest amount of mean height, root collar diameter, main root length and the number of lateral roots of seedlings. Suriyaprabha et al. [15] found that NSiO2 enhanced the germination and the growth of soybean under salinity stress.

Faba bean (*Vicia faba* L.) is widely grown in many parts of the world as a source of protein for both human and animal nutrition [16]. It is also traditionally used as a cover crop to recover nitrogen content and prevent erosion of the soil, and is appreciated for its good agronomic characteristics [17]. In addition to its high contents of protein and carbohydrates, *V. faba* is also rich in fiber, vitamins and minerals, and has a hypocholesterolaemic effect [18]. Although faba beans are consumed less in Western countries, they are one of the main sources of protein and energy for much of in Africa, Asia and Latin America [19]. Although there are a lot of references regarding interaction between salinity and silicon in higher plants, there is currently little information available about the possible beneficial effects of nano-silicon application to reduce salt stress damages in faba bean. Moreover, to the best of our knowledge, this is the first report on the application of nano-silicon in comparison to bulk silicon as potential agents for ameliorating salinity-induced plant stress on seed germination and growth characteristics of faba bean (*Vicia faba*), as a model for leguminous plants.

2. MATERIALS AND METHODS

Pot experiments were carried out in the greenhouse during winter season of 2010/2011, to investigate the effect of silicon particles (Si) and silicon nanoparticles (NSi, 40 nm) on germination, vegetative growth, and yield of faba bean (*Vicia faba* L.) plants grown under salt stress conditions. The experiment was arranged in a factorial design with 4 replications at NaCl levels of 0, 50, 100 and 200 mM. The tested Si and NSi concentrations were 0, 1, 2 and 3 mM.

2.1 Germination

The effects of NaCl, Si and NSi treatments on seed germination of faba bean were tested. The experiment was conducted at laboratory and arranged in completely randomized design (CRD) with 3 replications including 100 seeds in each replicates. Seeds were surface sterilized by dipping in 10 percent sodium hypochlorite solution for 10 minutes, then rinsed with sterilized distilled water and air-dried at an ambient temperature of 27ºC in the laboratory. Flat trays, of about 600 cm^2 size and 5 cm depth (a nursery seedling raising trays) with a single sheet of paper in the bottom to cover the drainage holes and filled with clean sand freely draining soil, were used. In each tray, 100 seeds were sowed in even rows at 2-3 cm depth, seeds were then covered with a little more sand. Si (in the form of Na_2SiO3) and NSi at 3 concentrations each (1, 2 and 3 mM) and NaCl (50, 100 and 200 mM), besides water as control treatment, were added gently to the trays and then placed in 25±2°C and 14/10 light/dark condition. Distilled water was applied to trays to prevent seed dryness. Germinated seeds were counted daily for 10 days and germination percentage (GP) was calculated in the last day. Calculating percentage germination Gp= (NG/NT) x100, where NG is the number of seeds germinated and NT is the total number of seeds. Germination rate (GR) is the number of seeds germinated per day and was calculated according to Naseri et al. [20] following the equation: GR = NG/DI, where, NG = number of germinated seeds in each count, and DI days to count. Seeds with 2 mm radical length considered as germinated seeds. The mean germination time (MGT) was calculated for each seed lot using the formula cited by Ellis and Roberts [21] given below:

$$MGT = \Sigma\ NG.DI/T$$

where, NG is the number of seeds newly germinating on the ti^{th} day of germination testing; DI is the days from the beginning of germination and T is the total number of seeds germinating during the experiment [20].

2.2 Preparing and Sowing of Seeds

Seeds of faba bean (cv. RM) were obtained from authorized agriculture company and were sterilized with 10% sodium hypochlorite solution for 10 minutes, washed three times with distilled water, and coated with N-fixing bacteria (*Rhizobium leguminosarum* strain Z25) using Tween 20 agent as an adhesive and scattering material. Identical seeds were then sown in plastic pots (30 cm inner diameter) filled with 10 kg sandy soil. Physical and chemical properties of the soil used in the study were recorded in Table 1. After sowing, irrigation was applied to supply seedlings with 100% available water, at two-day intervals until the seedlings reached the third leaf stage. Seedlings were then thinned to 3 plants/pot and pots were divided into four main groups for salt-stress treatments, with each group divided into seven subgroups for Si and NSi foliar application. Plants were fertilized with Sangeral complete fertilizer (Sinclair Horticulture LTD, England), in two equal portions; the first during the seedling stage and the second at the start of flowering stage. The fertilizer consists of macro elements, total nitrogen 20% N (4.4% Ammonia - 5.8% Nitrate - 9.8% Urea), Phosphorus (20% P_2O_5), Potassium (20% K_2O), Mg (0.012%) Sulphur (0.04%), and microelements (mg/kg) Fe (70), Zn (14), Cu (13), Mn (13), B (12) and Mo (12).

At the fourth leaf stage, irrigation solutions containing one of four levels of NaCl (0, 50, 100 or 200 mM) were used and were repeated after two weeks. To avoid osmotic shock due to high concentrations, plants were started with lower salt concentrations, then, salt concentration was increased on a daily basis until each group reached the concentration determined for it. Plants were then irrigated with tap water every three days with the addition of sodium chloride to the irrigation water every two weeks. Each pot was washed with 500 ml distilled water 2 days before the irrigation with saline solutions to prevent the increase in osmotic potential resulting from the accumulation of salts by the succession of irrigation procedures.

Just at the end of each salt treatments, foliar application of Si (as Si_2SO_3) and NSi (40 nm) in concentrations of 0, 1, 2, 3 mM was performed using a small pressure pump after adding Tween 20 (0.5%) as a wetting agent. The experiment consisted of 28 treatments (4 salt treatments with 3 Si treatments, 3 NSi treatments and water as control) and arranged in a factorial completely randomized design with 4 replicates for each treatment to make a sum of 112 pots.

Table 1. Physical and chemical analyses of the soil used in the experiment

Physical properties		Chemical properties			
Particle size distribution		CaCO3 (%)	0.41	**Soluble anions (meq/l)**	
Sand (%)	92.3	OM (%)	0.26	CO32-	0.22
Silt (%)	6.2	ES (dSm-1)	0.53	HCO3-	0.86
Clay (%)	1.5	**Soluble cations (meq/l)**		Cl-	1.83
Soil texture	(Sandy)	Ca2+	2.96	**Avail. elements (mg/kg)**	
		Mg2+	1.68	N	19.2
pH	8.01	Na+	2.04	P	8.3
		K+	0.21	Fe	2.4

Soil suspension (1 soil : 2.5 water)

2.3 Measurements

Three weeks after the second application of Si and NSi (about 100 days after germination), three replicates were taken from each treatment, and the following parameters were measured:

2.3.1 Growth characters

Plant height (cm); number of leaves/plant; leaf area (cm^2/plant) using leaf area meter; fresh and dry weights (g). Dry weights were recorded after oven drying at 70°C until constant weight.

Relative water content (RWC) was determined according to Bae et al. [22] as followes: Replicates of leaves were weighed for fresh weight (FW) and immediately soaked for 4 h in distilled water at room temperature under constant light, and the turgid weight (TW) was recorded. The leaves were then dried at 70°C and weighed to determine the dry weight (DW). The relative water content was calculated by substituting the following equation:

$$\text{Relative water content (\%)} = (FW-DW) / (TW-DW) \times 100$$

2.3.2 Yield and its components

At harvest time (nearly 150 days after sowing), number of pods/plant, number of seeds/plant, dry weight of pods (g), dry weight of seeds (g) and shelling percentage were recorded for each treatment. Harvest index was obtained according to Kobraee et al. [23] by dividing economic yield (grain dry weight) by biological yield (plant dry matter) multiplied by (100 * 0.25).

2.3.3 Elemental determination

Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and sodium (Na) were determined in dried samples of faba bean seeds as followes:

2.3.3.1 Nitrogen

In a mixture of the sulfuric and perchloric acid total nitrogen was determined by the micro-Kjeldahl method [24].

2.3.3.2 Phosphorus

For total inorganic phosphorus estimation, 0.5 g of plant material was extracted in 8 ml trichloroacetic acid (6%) and centrifuged for 15 min at 18000g. phosphate in supernatant was determined colorimetrically after adding 5 mol sulphuric acid, 2.5% ammonium molybdate and 0.25% 1,2,4-amino- naphthol-sulphonic acid solution. After 15 min incubation at 37°C the absorbance was measured at 660 nm [25].

2.3.3.3 Potassium and sodium

For Measurements of K and Na concentrations, the leaves were dried in 60°C for 48 h. Then 1 g of leaves was powdered and burned in 560°C to obtain ash then ashes digested in 10 ml of 1N HCL. The concentration of K and Na in the digested samples was determined using a flame photometer (Model 420, Sherwood, Cambridge, UK) [26].

2.3.3.4 Calcium

For calcium (Ca) analysis, dried samples were ground to pass a 20-mesh sieve and digested with a mixture of H_2SO_4-H_2O_2 according to Lachica et al. [27]. Calcium was measured on the acid-digested samples by atomic absorption spectrophotometry in a Perkin Elmer Analyst 800 (Perkin Elmer Inc., Wellesley, MA) spectrophotometer equipped with a PE6017 lamp, and measured at 422.7 nm.

2.4 Statistical Analysis

The collected data were analyzed statistically using factorial completely randomized design and analysis of variance (ANOVA) according to Gomez and Gomez [28] with the aid of COSTAT computer program. Treatment means were compared using the least significant difference test (LSD) at 5% level.

3. RESULTS AND DISCUSSION

3.1 Seed Germination

It is well known that seed germination provides a suitable foundation for plant growth, development and yield. In the present experiment application of NSi enhanced seed potential by increasing the characteristics of seed germination (Table 2). Parameters of seed germination were increased with increasing levels of NSi up to 2 mM. Among the treatments, application of 2 mM of NSi proved best by giving the highest values for percent seed germination, germination rate and germination mean time.

The collected results revealed that germination of faba bean seeds was strongly affected by both salt and silicon treatments. Increased salt concentration caused a decrease in germination percent (Table 2). Strong reduction in germination (-18%) was observed mainly at the highest level of salt concentration as compared to control treatment. Conversely, all treatments of Si and NSi increased germination percentage (GP) of the seeds under 0% NaCl treatment with most increase in GP at Si2 and NSi2 treatments.

At 50 mM salinity, NSi2 was the only treatment that increased GP (+4%) while other treatments did not show any significant change as compared to control treatment. It is well observed that the exogenous application of Si or NSi decreased the reduction of germination resulted from salt treatments. In this regard, earlier studies showed that high concentration of salts have an adverse effect on germination of seeds. In addition, many investigators have reported retardation of seed germination at high salinity [29]. The adverse effects of high concentration of salts on seed germination may be attributed to the osmotic retention of water and to specific ionic effects on the protoplasm of the embryo. It has been found that germination percentage was reduced with high NaCl concentrations [30].

Data indicate also that Si and NSi treatments enhanced germination attributes. These results agree with the findings of Adhikari et al. [31]

Table (2). Effect of silicon and nano-silicon on germination (%), germination rate, mean germination time of faba bean seeds under different levels of salinity stress

Silica treatments	Salinity levels (mM)											
	00	50	100	200	00	50	100	200	00	50	100	200
	GP (%)				GR (day)				MGT			
Cont	88.6	86.5	80.4	72.6	8.21	7.42	4.65	2.52	3.13	3.34	3.55	3.87
Si1	92.3	90.4	85.3	82.2	9.32	8.23	5.53	3.45	2.74	3.04	3.26	3.45
Si2	94.6	91.3	86.7	83.5	8.52	7.82	4.85	3.03	2.92	3.25	3.46	3.56
Si3	90.4	88.5	84.6	78.8	7.74	6.84	4.16	2.35	3.44	3.42	3.53	3.92
NSi1	93.3	92.2	90.5	86.5	9.75	8.82	5.76	3.85	2.52	2.75	3.14	3.35
NSi2	95.1	98.7	91.1	88.5	8.64	8.06	5.11	3.62	2.84	2.94	3.32	3.45
NSi3	92.8	90.2	85.6	84.7	7.81	6.85	4.38	3.05	3.36	3.47	3.45	3.76
LSD (5%)	2.24	2.68	4.75	8.66	1.11	1.75	0.86	0.70	0.55	0.48	0.32	NS

Mean of main effects

Treat	mM	Germination characteristic		
		GP	GR	MGT
Salt treatments	00	92.4	8.67	2.99
	50	91.1	7.72	3.17
	100	86.3	4.92	3.38
	200	82.4	3.12	3.62
	LSD 5%	5.16	3.22	0.25
Silicon treatments	00	82.0	5.70	3.47
	Si1	87.6	6.63	3.12
	Si2	89.1	6.06	3.29
	Si3	85.6	5.27	3.58
	NSi1	90.6	7.05	2.94
	NSi2	93.4	6.36	3.14
	NSi3	88.3	5.52	3.51
	LSD 5%	3.55	1.05	0.35

who reported that application of 8 g/ L of NSi increased rice GP, GMT and GI significantly as compared with untreated control plants. Other studies reported better germination of rice seeds [32] and corn grains [33] when treated with nano-silicon, the stimulation effect of NSi on corn germination was more pronounced than that induced by conventional Si [34].

The present study showed also that GR decreased with increasing salinity level, while Si and NSi treatments improved GR, either in presence or absence of NaCl application. At 200 mM NaCl, the decrease in GR of Si and NSi untreated seeds reached about 51% as compared with control Table 2. It is well observed that Si and NSi treatments overcome the harmful effect of salinity stress on GR. Most improvement in GR was recorded at Si1 and NSi1 treatments, followed by Si2 and NSi2, while Si3 and NSi3 caused a significant decrease in GR as compared with control treatment. At 200 mM NaCl, Si1 and NSi1 improved the GR of faba seeds by about 37% and 53%, respectively, as compared with GR values at same NaCl treatment without Si or NSi. In this regard, Haghighi et al. [11] showed that germination speed index of tomato seeds was decreased with increasing salinity. It is well known that the activities essential for seed germination need to have enough water for faster germination. If the water absorption is impaired as in the case of salinity, germination goes slowly [20]. In a previous study, seed germination and growth rate of soybean [33] and cucumber [34] seeds were enhanced with increasing available Si and NSi content in salt stress conditions. In this concern, Si and NSi were reported as activators for the expression of defense genes during salt stress [35]. The positive effect of Si and NSi in seed germination could be attributed to reduced oxidative damages induced by salt stress. Lipid peroxidation, which is a result of salinity stress, was inhibited by Si because it causes an increase in some scavenging ROS enzymes like SOD and catalase [36] and [37]. In earlier studies, [38] and [39] found that seed germination rate was higher with NSi than with bulk Si, most probable because nanoparticles could penetrate into the seed coat and exert a helpful effect on the process of germination, while the bulk particles, having a larger size, cannot easily enter the same pathway, therefore may accumulate in the pores of a seed coat and clog up water and oxygen transition.

On the whole, lower mean germination time (MGT) represents earlier germination. The results recorded in Table 2 revealed that salt treatments delayed the germination time of faba bean seeds and thus MGT exhibited higher value than that of control treatment. With Si or NSi, salt-treated seeds had lower values of MGT than that recorded for salt-treated seeds without Si or NSi treatments. Thus, exposure of seeds to 1 or 2 mM of Si bulk or Si nanoparticles obtained the lowest MGT but higher concentrations did not improve it. The present results indicate that Si1 and Si2 reduced MGT in salt-untreated seeds by 13% and 6% in comparison to the untreated control, respectively. Similarly, NSi1 and NSi2 reduced MGT by 19% and 10%, respectively. While, Si3 and NSi3 treatments did not contribute to a reduction of MGT as compared with the control Table 2. In this regard, Zheng et al. [40] reported significantly positive effect of nanosized elements on MGT of spinach seeds.

Recent studies [41] and [42] found that application of NSiO2 significantly enhanced seed germination, mean germination time, seed germination index, seed vigour index and seedling fresh and dry weight. Reasons for that enhancement are reported by Lei et al. [43] as increasing seed ability of absorbing and utilizing water and fertilizer, promoting seed antioxidant system, reducing anti-oxidant stress by reducing superoxide radicals and increasing activity of some enzymes such as superoxide dismutase, ascorbate peroxidase, guaiacol peroxidase, and catalase [43].

3.2 Vegetative Growth

Data in Table 3 indicated that the highest salinity level decreased plant height, leaf number and leaf area by about 13%, 35% and 39%, respectively, as compared with control treatment. Similarly, increased levels of NaCl corresponded with decreased plant fresh and dry weights Table 4. The lowest values of growth parameters were recorded at the highest level of salt concentration (200 mM). While at low salt stress (50 mM) no significant effect on fresh and dry weights was observed. It is also clear that relative water content (RWC) was decreased significantly with NaCl treatments. Similar trend was observed for plant fresh and dry weights. These results are in agreement with those reported by Hanafy Ahmed et al. [44]. The recorded suppression of plant growth under saline conditions was ascribed to decreased availability of water and/or to toxicity of sodium chloride [45]. Reduced dry weight under salinity stress was attributed to inhibition of food formation and translocation, inhibition of some metabolic processes, inhibition of chloroplast formation, production of ethylene and abscisic acid, and decreasing nutrient absorption [46].

Recorded data showed that Si and NSi increased plant height, number of leaves and leaf area as compared with Si untreated control plants. Growth parameters increased with 1 and 2 mM of Si or NSi treatments either under normal condition or salinity stress condition. Most effects of Si and NSi were observed at low levels of salt stress Table 3. Under higher level of salt stress (200 mM) only Si2 and NSi2 treatments improved plant height and leaf area.

Fresh and dry weights increased with Si1and Si2 but did not chang significantly with higher levels Table 4. Similarly NSi1 and NSi2 improved fresh and dry weights either in the presence or absence of salt stress. The increase in fresh and dry weights under NSi treatments was more observed than that recorded with Si treatments.

It was clear that Si3 and NSi3 had no significant effects on fresh and dry weights as compared with control treatment. Moreover, Si and NSi treatments increased significantly RWC Table 4. The hazardous effect of 50 and 100 mM salinity levels on growth parameters was alleviated with Si and NSi treatments.

It was clear that, water content of 50 and 100 mM NaCl treated plants was increased with Si3 and NSi3 treatments. In this regard, Gong et al. [47] reported improved water economy and dry matter yield of wheat plants by Si application. Bradbury and Ahmad [48] reported that salt tolerance of wheat (*Triticum aestivum*) and mesquite (*Prosopis juliflora*) could be markedly enhanced by the addition of small amounts of soluble silicon. Some evidence shows that silicon may involve in the osmotic adjustment of many plant species [49]. In this regard, Shahzade [50] reported that in *Vicia faba* the treatment of 75 and 100 mM NaCl plus 1 mM silicon increased biomass to 14% and 18% compared with the salt treatment without silicon.

Table 3. Effects of silicon and nano-silicon on plant heights, number of leaves and leaf area of faba bean plants grown under different levels of salinity stress

Silica treatments	Salinity levels (mM)											
	00	50	100	200	00	50	100	200	00	50	100	200
	Plant height (cm)				No. leaves/plant				Leaf area/plant (cm^2)			
Cont	84.3	85.2	79.3	73.7	28.1	27.6	22.7	18.5	595	584	520	364
Si1	89.6	88.4	82.5	76.6	32.2	32.7	25.3	21.6	658	648	554	426
Si2	91.2	93.3	84.5	80.8	35.5	34.6	27.8	22.5	674	668	578	467
Si3	96.5	95.8	88.2	83.5	37.5	35.8	29.6	23.7	683	685	607	492
NSi1	93.6	94.8	85.7	78.5	35.6	35.4	30.1	24.5	665	658	618	486
NSi2	99.5	98.2	90.1	85.5	39.8	37.5	33.7	27.4	712	698	632	495
NSi3	86.4	84.6	76.4	74.4	31.5	30.7	24.8	20.2	616	608	538	411
LSD (5%)	4.55	5.54	4.63	5.28	3.63	4.52	2.05	2.16	45.8	42.3	25.9	38.8

Mean of main effects

	mM	Growth parameters		
		Plant height	No. leaves	Leaf area
Salt treatments	00	91.6	34.3	657.6
	50	91.5	33.5	649.9
	100	83.8	27.7	578.1
	200	79.0	22.6	448.7
	LSD 5%	3.12	3.42	66.5
Silicon treatments	00	80.6	24.2	515.8
	Si1	84.3	27.9	571.5
	Si2	87.5	30.1	596.8
	Si3	91.0	31.7	616.7
	NSi1	88.2	31.4	606.8
	NSi2	93.3	34.6	634.3
	NSi3	80.5	26.8	543.3
	LSD 5%	3.12	2.35	45.6

The mitigation effect of Si under saline conditions on plant growth is reported in the literature [6]. According to Ma and Yamaji [51], the positive effect of Si is because of its deposition in the roots, apoplastic bypass flow decreases and provides binding sites for metals, resulting in decreased uptake and translocation of toxic metals and salts from roots to shoots. In an earlier study, increased K uptake and decreased Na uptake by addition of Si in bean was the major mechanisms responsible for better growth of plants under salinity [50].

Data in Tables 3 and 4 showed clearly that, low concentrations of Si and NSi were more effective on plant growth at all salinity levels than high ones. These results agree with Parveen and Ashraf [8], who found that exogenously applied Si significantly enhanced plant water use efficiency (WUE), and slightly increased photosynthetic rate under saline stress condition in wheat and maize. This is likely due to the role of silicon in the enzyme activities and biochemical processes in plant tissues [11].

3.3 Yield Components

Yield components of faba bean including number of pods per plant, number of seeds per pod and the weight of one hundred seeds play an important role in determining the final crop yield. In the present study, data registered in Table 5 revealed that increasing salinity level caused a gradual decrease in number of pods and seeds per plant and the weight of 100 seeds. Similarly, salinity stress significantly reduced pod and seed weights per plant but increased shelling percentage Table 6, the reduction was much greater at salinity level of 200 mM than at 100 or 50 mM. In this concern, 200 mM NaCl treatment caused a reduction of about 54%, 45% and 46% in number of pods, number of seeds and 100 seed weight as compared with control, respectively. Reductions in pod weight per plant and seed weight per plant at 200 mM were severe and reached about 50% and 51% as compared to control, respectively. In contrast, shelling percentage increased under salinity stress and showed a high value at 100 mM of NaCl, under which shelling percentage increased by about 35% over control treatment. The reduction in yield attributes may be attributed to the inhibiting effects of salinity on some metabolic processes in plant tissues [46]. It was found that at the high salinity level, salts may build up in the apoplast and dehydrate the cell and inhibit enzymes in cytoplasm involved in carbohydrate metabolism, or may exert a direct toxic effect in chloroplast and photosynthetic processes [45].

On the other side, Si and NSi applications, particularly at 1 and 2 mM, increased all yield components and decreased shelling percentage either in saline treated or untreated plants Tables 5 and 6. In this regard, Si2 treatment caused an increase in the number of pods per plant, number of seeds per plant and weight of 100 seeds by about 46%, 32% and 12%, respectively, as compared to control Table 5.

The corresponding increases with NSi2 treatment were about 70%, 39% and 10%, respectively. Concerning dry weights of pods and seeds, the Si2 treatment caused an increase of about 24% in pod dry weight and about 28% in seed dry weight, while NSi2 treatment caused an increase of about 32% and 37% in pod dry weight and seed dry weight, respectively. In this concern, silicon was reported to enhance growth and yield of many of higher plants particularly under biotic and a biotic stresses. A number of possible mechanisms are proposed by which Si can increase resistance of plants against salinity stress the major yield limiting factor in arid and semiarid areas [19].

The present study showed clearly that salinity had a negative effect on the yield and its components of *V. faba* plants. These results confirm the findings of Sabetteymoori et al. [52] who reported that increasing salinity level reduced the yield of sesame plant. Also, Sakr et al. [53] found that salinity reduces the number of seeds per plant of faba bean. It is well known that flowering stage is a critical and sensitive to salinity stress [54], consequently, total pods per plant is reduced by salinity [55]. According to Munns and Tester [45], salinity stress affects flowering of soybean plant and reduces number of pods. Parsa et al. [56] reported that high salinity stress caused a weight loss of 100-seed.

The reduction in 100-seed weight under salinity stress was attributed to the inhibition in uptake and transfer of nutrition materials during the growth of grains and their filling periods. Moreover, salinity may cause a severe damage to ovary and resulted in fruit drop and decreases the yield [45].

Table 4. Effects of silicon and nano-silicon on fresh weight, dry weight and water content of faba bean plants grown under different levels of salinity stress

Silica treatments	Salinity levels (mM)											
	00	50	100	200	00	50	100	200	00	50	100	200
	FWt (g)				DWt (g)				RWC (%)			
Cont	31.3	32.1	26.3	22.2	6.25	6.33	5.63	4.81	92.3	84.5	75.2	60.4
Si1	33.7	33.5	29.8	24.5	7.13	6.86	6.06	5.34	94.5	90.5	80.6	67.4
Si2	35.5	34.3	31.3	26.5	9.08	8.12	7.82	6.16	95.7	91.7	84.8	73.7
Si3	37.8	35.1	32.8	27.9	9.85	9.24	8.75	6.76	93.4	92.8	82.5	70.2
NSi1	36.4	34.9	31.2	28.5	8.65	8.72	7.86	6.27	92.3	90.4	85.4	74.1
NSi2	39.2	38.2	35.1	30.1	11.5	10.4	9.18	7.56	96.2	92.5	86.6	78.6
NSi3	32.5	31.0	28.3	23.2	7.85	7.26	5.94	5.58	93.7	90.6	83.3	73.4
LSD (5%)	2.25	2.15	2.26	2.12	2.33	2.45	2.08	1.18	1.60	2.11	3.27	3.18

Mean of main effects

	mM	Growth parameters		
		Fwt	Dwt	RWC
Salt treatments	00	35.2	8.62	94.1
	50	34.2	8.13	90.4
	100	30.7	7.32	82.6
	200	26.1	6.07	71.1
	LSD 5%	2.15	0.85	4.27
Silicon treatments	00	27.9	5.76	78.1
	Si1	30.4	6.35	83.3
	Si2	31.9	7.79	86.5
	Si3	33.4	8.65	84.7
	NSi1	32.8	7.87	85.6
	NSi2	35.7	9.66	88.5
	NSi3	28.8	6.67	85.3
	LSD 5%	2.46	1.15	2.44

Table 5. Effects of silicon and nano-silicon on number of pods/plant, number of seeds/plant and 100 seed weigh of faba bean plants grown under different levels of salinity stress.

Silica treatments	Salinity levels (mM)											
	00	50	100	200	00	50	100	200	00	50	100	200
	No. pods/plant				No. seeds/plant				100 seed weight (g)			
Cont	08.2	06.7	04.8	03.1	20.2	18.7	15.3	10.4	242	245	235	132
Si1	08.8	07.3	05.5	04.2	22.4	20.4	16.7	12.2	255	252	245	155
Si2	11.4	09.9	07.3	04.9	26.5	23.5	19.8	15.3	282	265	253	154
Si3	08.4	06.4	05.1	03.9	23.3	17.7	15.9	13.1	261	252	242	146
NSi1	10.5	08.5	06.5	04.7	22.2	21.3	16.6	12.7	258	257	240	151
NSi2	12.1	11.2	09.4	06.2	28.4	24.2	20.3	16.6	290	268	246	138
NSi3	09.2	08.1	06.2	04.4	24.2	20.5	15.4	11.8	258	248	232	128
LSD (5%)	2.04	2.12	2.11	2.14	3.23	2.65	2.27	2.18	9.12	6.15	6.38	9.55

Mean of main effects

	mM	Yield attributes		
		No.pods/plant	No. seeds/plant	100 seed Wt
Salt treatments	00	9.82	23.88	263.7
	50	8.34	20.92	255.2
	100	6.45	17.14	241.8
	200	4.48	13.15	143.4
	LSD 5%	1.66	2.45	26.8
Silicon treatments	00	5.73	16.15	213.5
	Si1	6.45	17.92	226.7
	Si2	8.37	21.27	238.5
	Si3	5.95	17.54	225.2
	NSi1	7.55	18.20	226.5
	NSi2	9.72	22.37	235.5
	NSi3	6.97	17.97	216.5
	LSD 5%	2.12	2.16	15.15

Table 6. Effects of silicon and nano-silicon on weight of pods/plant, weight of seeds/plant and shelling% of faba bean plants grown under different levels of salinity stress

Silica treatments	Salinity levels (mM)											
	00	50	100	200	00	50	100	200	00	50	100	200
	Pod dwt (g/plant)				Seed dwt (g/plant)				Shelling (%)			
Cont	16.4	14.6	11.1	8.2	13.1	11.4	08.1	6.3	20.1	21.9	27.1	23.2
Si1	18.2	16.4	12.7	9.3	14.7	13.1	09.6	7.4	19.2	20.1	24.4	20.4
Si2	20.6	17.2	14.2	10.3	16.9	13.7	10.7	8.3	17.9	20.3	24.6	19.4
Si3	17.8	15.3	11.4	8.9	14.4	11.9	08.3	7.1	19.1	22.2	27.2	20.2
NSi1	19.1	16.8	14.2	10.5	15.6	13.3	10.6	8.5	18.3	20.8	25.3	19.1
NSi2	22.2	17.8	15.3	11.2	18.4	14.2	11.8	8.8	17.1	20.2	22.8	21.4
NSi3	20.4	16.3	13.8	9.7	16.7	12.6	10.5	7.7	18.2	22.6	23.9	20.6
LSD (5%)	2.06	1.32	2.11	1.88	2.25	1.15	1.27	1.55	2.0	1.82	2.16	2.44

Mean of main effects

	mM	Pods Dwt	Seed Dwt	Shelling%
Salt treatments	00	19.24	15.68	18.55
	50	16.34	12.88	21.15
	100	13.24	9.94	25.04
	200	9.73	7.72	20.61
	LSD 5%	2.66	2.11	2.24
Silicon treatments	00	12.57	9.73	23.07
	Si1	14.15	11.20	21.03
	Si2	15.57	12.40	20.55
	Si3	13.35	10.42	22.18
	NSi1	15.15	12.00	20.87
	NSi2	16.62	13.30	20.37
	NSi3	15.05	11.87	21.33
	LSD 5%	2.18	2.23	2.05

Registered data showed clearly that Si and NSi applications caused an increase in the yield of salt treated or untreated faba bean plants. This result is in agreement with that reported by [19] and [57]. The increase in seed yield at mild saline condition after silicon amendment may indicate an improvement in the translocation of minerals and metabolites necessary for seed setting. The role of silicon as a beneficial mineral nutrient for reproductive growth of plant is well documented [58]. Generally, Increased K uptake and decreased Na uptake by Si treatments was reported to be the major mechanisms responsible for better growth and yield of plants under salinity [6].

It has been observed that supplemental silicon improves yield and reduce the plant biotic and abiotic stresses [4]. Some studies have shown that Si is effective in mitigating salinity in different plant species, such as cucumber [59], maize [60], tomato [61], and wheat [62]. Some possible mechanisms through which silicon may increase salinity tolerance in plants include: immobilization of toxic sodium ion [63], reduced sodium uptake in plants and enhanced potassium uptake [7] and higher potassium, sodium selectivity [64].

The harvest index (HI) was affected significantly by salinity stress (Fig. 1). In this regard HI values were decreased with increasing salinity level. At 200 mM of NaCl, the harvest index of silicon untreated plants was decreased by about 38.5% as compared to 0 mM NaCl treatment. It is clear from the data in the same figure that Si and NSi treatments had a significant enhancing effect on seed yield of faba bean therefore the harvest index values were increased with Si and NSi treatments under different salt treatments. The present study showed that Si1 and NSi3 treatments were the most effective in reducing the harmful effect of salinity on harvest index. In this regard Kobraee et al. [23] stated that abiotic stress decreased harvest index. Silicon treatment, on the other side, causes an improvement in the harvest index of different crops under salinity stress [65]. Moreover, Kardoni et al. [19] and Parande et al. [54] found that Si treatments improved yield, yield components and harvest index of faba bean under salt stress conditions. In a study by

Jaberzadeh et al. [66] they found that water deficit stress decreased harvest index while Titanium dioxide nanoparticles caused the maximum harvest index, whereas titanium oxide (bulk) and control treatments were similar [66].

3.4 Mineral Contents of Faba Bean Seeds

Data recorded in Table 7 indicates that faba bean seeds grown under low (50 mM) and moderate (100 mM) salt stress had higher contents of N, P than those of salt unstressed control seeds. It is laso clear that the 50 mM salt treatment caused an increase in Ca and K concentrations in faba seeds. In contrast, the high salinity level (200 mM) caused significant decreases in N, P, Ca and K in plant seeds as compared with control treatment. The corresponding decrease in the mentioned elements in seeds at 200 mM treatment were about 3.5%, 7%, 22% and 15% of control seeds, respectively. Na content in seeds, on the other side, showed a linear increase with increasing salinity level to reach its maximum value at 200 mM salt treatment, at which Na increased by about 17% of control seeds. These results caused an observed decrease in the K/Na ration in faba seeds at 100 and 200 mM treatments as compared with the K/Na ratio of control seeds.

Data in the same table revealed that Si and NSi treatments caused a slight decrease in N, Ca and Na concentrations in faba seeds as compared to Si and NSi untreated seeds. Seed K content on the other side, showed a noticeable increase under all Si and NSi treatments. The highest values of K% in seeds were recorded at Si2 and NSi2 treatments. At which K were increase by about 16% and 15%, respectively, compared with control treatments.

As for the interaction effect of salt stress and silicon treatments on elemental concentrations in faba bean seeds, the results recorded in Tables 8 and 9 revealed that both factors showed some effects on mineral contents. The results in Table 8 shows that Si and NSi treatments enhanced N and P contents in salt treated seeds, particularly at 50 and 100 mM salt treatments. While, at 200 mM NaCl treatment N (%) decreased in Si and NSi treated seeds. The most enhancing effect on N (%) under salt stress was observed at Si1 and NSi1 treatments. Both treatments improved N (%) at 50 and 100 mM salt treatments, while othe Si and NSi treatments improved N (%) only at 50 mM treatment compared to same Si and NSi treatments in the absence of salt stress. It is clear, also, that Si and NSi treatments caused an observed increase in Ca and K content of the 50 mM NaCl treated seeds. While, the 200 mM salt treatment showed a significant decrease in Si and NSi treated seeds.

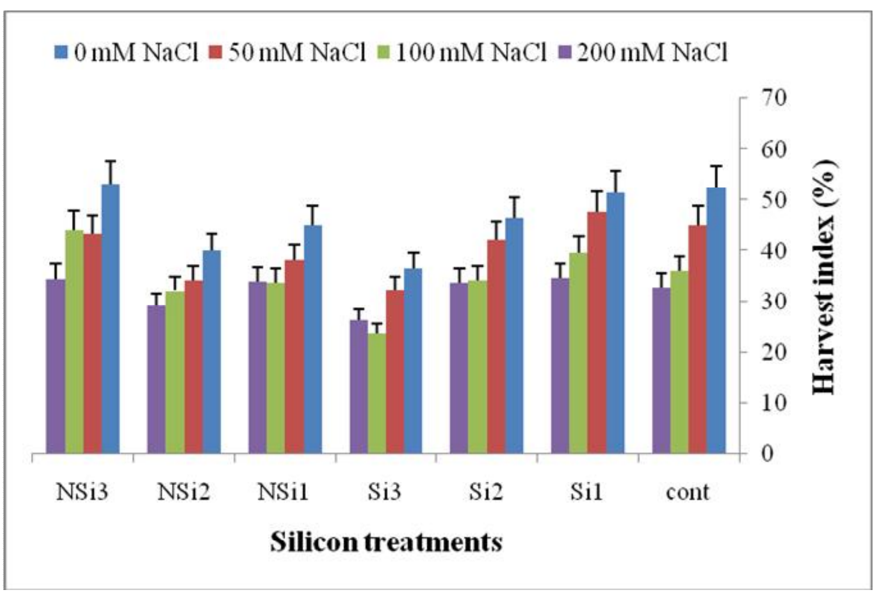

Fig. 1. Effects of silicon and nano-silicon on harvest index (HI) of faba bean crop under different levels of salinity stress

Data shows that all Si and NSi treatments caused a significant increase in K content of slat stressed faba seeds Table 9. Under all salinity levels, the most effective treatments of silicon were Si2 and NSi2. At 50 mM salt treated seeds, Si2 caused an increase of about 16% and NSi2 caused an increase of about 13% in seed K content as compared with seeds under the same salt treatment without Si or NSi application. The corresponding increase in K at 200 mM salt treatment were about 25% and 21%, respectively. It seems that the positive effect of Si and NSi on K (%) was more pronounced at high than low salt stress.

Sodium content of faba seeds under salinity stress, on the other side, was decreased with Si and NSi application. Si3 and NSi2 treatments were the most active in reducing Na (%) of salt stressed seeds. These results reflect the

Table 7. Effects of salinity stress and silicon treatments on mineral contents of faba bean seeds

	mM	N%	P%	Ca%		mM	K%	Na%	K/Na
Salt treatments	00	3.27	0.29	1.69	Salt treatments	00	3.49	2.14	1.62
	50	3.56	0.33	1.80		50	3.72	2.19	1.71
	100	3.51	0.30	1.46		100	3.38	2.32	1.46
	200	3.16	0.27	1.32		200	2.97	2.50	1.19
LSD5%		0.25	0.16	0.24	LSD5%		0.25	0.22	0.24
		N%	**P%**	**Ca%**			**K%**	**Na%**	**K/Na**
Silicon treatments	Con	3.58	0.27	2.04	Silicon treatments	Con	3.14	2.63	1.20
	Si1	3.42	0.30	1.79		Si1	3.35	2.42	1.39
	Si2	3.36	0.33	1.56		Si2	3.64	2.21	1.65
	Si3	3.18	0.27	1.35		Si3	3.25	2.13	1.54
	NSi1	3.45	0.31	1.61		NSi1	3.36	2.36	1.44
	NSi2	3.42	0.33	1.45		NSi2	3.61	2.16	1.68
	NSi3	3.22	0.27	1.21		NSi3	3.41	2.15	1.58
LSD5%		0.17	0.15	0.20	LSD5%		0.17	0.15	0.14

Table 8. Effects of silicon (Si) and nano-silicon (NSi) on N, P and Ca percentages in faba bean seeds under different levels of salinity stress

Treat.	N (%)				P (%)				Ca (%)			
	00	50	100	200	00	50	100	200	00	50	100	200
Con	3.15	3.82	3.92	3.44	0.26	0.28	0.29	0.26	2.06	2.22	2.02	1.86
Si1	3.24	3.37	3.83	3.23	0.29	0.32	0.31	0.28	1.85	2.00	1.77	1.52
Si2	3.35	3.71	3.22	3.16	0.32	0.35	0.33	0.30	1.64	1.76	1.51	1.34
Si3	3.27	3.42	3.16	2.86	0.25	0.31	0.28	0.25	1.35	1.52	1.35	1.16
NSi1	3.26	3.38	3.87	3.28	0.31	0.35	0.33	0.26	2.02	2.12	1.18	1.12
NSi2	3.37	3.75	3.35	3.21	0.36	0.38	0.30	0.28	1.66	1.72	1.23	1.17
NSi3	3.25	3.48	3.22	2.92	0.26	0.32	0.26	0.24	1.26	1.29	1.17	1.11
LSD5%	0.12	0.25	0.11	0.18	0.05	0.06	0.06	NS	0.13	0.16	0.19	0.23

Table 9. Effects of silicon (Si) and nano-silicon (NSi) on K, Na and K/Na ration in Faba bean seeds under different levels of salinity stress

Treat.	K (%)				Na (%)				K/Na			
	00	**50**	**100**	**200**	**00**	**50**	**100**	**200**	**00**	**50**	**100**	**200**
Con	3.35	3.51	3.12	2.58	2.33	2.52	2.63	3.02	1.43	1.39	1.18	0.81
Si1	3.42	3.64	3.29	3.05	2.28	2.30	2.42	2.66	1.50	1.58	1.35	1.14
Si2	3.63	4.06	3.62	3.24	2.06	2.15	2.20	2.43	1.76	1.88	1.64	1.33
Si3	3.40	3.59	3.24	2.75	2.00	2.05	2.17	2.24	1.70	1.75	1.49	1.23
NSi1	3.43	3.67	3.30	3.02	2.21	2.25	2.40	2.58	1.55	1.68	1.37	1.17
NSi2	3.68	3.95	3.68	3.12	2.10	2.00	2.18	2.36	1.75	1.97	1.68	1.32
NSi3	3.51	3.66	3.42	3.04	2.05	2.10	2.22	2.26	1.71	1.74	1.54	1.34
LSD5%	0.17	0.12	0.14	0.25	0.13	0.11	0.13	0.26	0.18	0.22	0.21	0.23

enhancing effect of Si and NSi treatments on K/Na ratios. It is clear that salt stress decreases K/Na ratio, while Si and NSi application increased this ratio. In an early study, Liang et al. [63] reported a significant increase in K uptake and decrease in Na uptake under salt stress when Si was included because of increased activity of plasma membrane H-ATPase. K/Na ratio was significantly lower under salinity stress when Si was not applied. Silicon application enhanced K/Na selectivity ratio in faba bean thus enhancing pod yield. They found also that the application of silicon in the high salinity soil increased the K/Na ratio.

Nitrogen (N), Phosphorus (P), Potassium (K) Calcium (Ca) are very important elements for membrane structure, cell division, stomatal function, and plant growth cell-wall synthesis, direct or signaling roles in systems involved in plant defense and repair of damage from biotic and abiotic stress, and rates of respiratory metabolism and translocation [67].

Early studies on the interactive effect of macronutrients (N, P, K+, Ca2+, Mg2+, and S) and salinity on the growth of cowpea, tomato, clover, and wheat showed that, for a given salinity level, increasing salt concentration caused a significant reduction in the nutrient contents of seeds and fruits [67]. In more recent study Hellal et al. [68] reported that there was an obvious gradient between potentially toxic (Na and Cl) and essentially needed elements (K, Mg, Ca, P and S) in the seeds of plants grown under salinity stress. The exclusion of Na+ ions and a higher K: Na ratio in bean plants grown under saline conditions have been confirmed as important selection criteria for salt tolerance [69]. In an early study, it has been indicated that application of Si significantly increased the contents of P and K, and the K/Na ratio and decreased Na ion contents of salt-affected faba seeds [68]. Therefore, the results shown in the present study agree with those reported by Abdelhamid et al. [69] on faba bean which indicate that salt tolerance is associated with an enhanced K: Na discrimination trait.

4. CONCLUSION

In conclusion, current study reveal that salinity stress resulted in considerable decrease in seed germination, vegetative growth and yield of faba bean. The results highlight the role of Si and NSi in regulating salinity responses, and indicate that silicon and nano-silicon could protect faba bean plants against the hazardous effect of salinity. There were no meaningful differences between the Si and NSi applications; both forms of silicon were effective at lower levels in most measured characteristics. However, the study invites researchers to find out the interaction mechanism between nanosilica and plants which establishes that NSiO2 could be used as a fertilizer for the crop improvement.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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