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ORIGINAL PAPER

Silicon Utilization Efficiency of Different Wheat Cultivars in a Calcareous Soil

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Abstract
The main purpose of this study was to investigate the effects of different silicon levels and sources on the efficiency of acquisition and utilization of silicon in seven wheat cultivars in a calcareous soil. The treatments consisted of silicon additions to the soil (control, 200, 400, and 1000 mg/kg as potassium silicate and 0, 50, and 100 mg/kg as nanoparticles) and seven wheat cultivars (*Gonbad, Shiroudi, Shiraz, Mahdavi, Marvdasht, Bahar, and Parsi*). The factorial experiment was carried out in three replications. The results showed that the application of silicon at different levels and from various sources, as well as wheat cultivars and their interactions with the silicon treatments, led to significant differences ($p \leq 0.01$) in the root and shoot dry weights, the silicon concentration in the root and shoot, and the total silicon in the shoot. In addition, there was a significant relationship between the silicon level/source and wheat cultivars with all efficiency indices (at level of 1%). The results also show there is a significant ($p \leq 0.01$) relationship between shoot silicon efficiency and silicon acquisition efficiency (0.72). Therefore, considering the role of silicon in stress alleviation, its application in wheat cultivars with higher acquisition efficiency can help the plant growth.

Keywords Wheat · Utilization efficiency · Acquisition · Silicon · Silicon Nano-particle · Stress

1 Introduction

Silicon forms 28% of the earth's crust, in which it is the second most abundant mineral after oxygen [1]. In the environment, silicon is found in the form of clay minerals and amorphous silicates and it is the most important source of silicon for plants [2]. However, the most immediate source of soluble silicon is adsorbed silicon, which is maintained through the exchange of anionic ligand and which finally supplies the silicon in the soil solution, which can be absorbed into the form of mono-silicic acid or anionic acid [3]. Although silicon is an abundant element in the soil, due to the aeration/degradation resistance of silicon-containing minerals, the level of available silicon is low in the soil solution, and its absorption by plants therefore depends on the ability of the soil to provide silicon [4].

In modern agriculture, silicon is considered to be a functional element for a number of plants, especially for gramineous species [5]. There is an argument that it should be considered essential, based on the fact that a significant silicon deficiency will influence plant growth, development, and reproduction [6]. According to report [7], silicon should be regarded as an essential element for higher plants. An investigation of wheat nutrition with silicon-based fertilizers indicates that crop yield is increased and the quality is improved [8]. Regardless of the necessity of silicon, its role in the alleviation of the biological and non-biological stresses, as well as in the balance of nutrients in other plants, has been proven [9, 10].

In recent decades, in line with sustainable agriculture goals, the utilization of the genetic potential of plants to increase the growth and nutrient acquisition is one of the important alternatives to the use of fertilizers. It is recommended to protect environmental and economic health [11, 12]. The capability of various plant genotypes in nutrient acquisition and utilization has been highlighted by many researchers. The differences in their efficiency affect the nutrient acquisition by the root and/or nutrient utilization by the plant, the relative importance of

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which varies depending on the plant species and the nutrient [13]. Efficiency is defined as the ratio of output (economic yield) to input (fertilizer) for a complex process or system. Accordingly, the efficiency can be improved by selecting a proper crop management. Elemental utilization efficiency has a significant positive correlation with seed yield of crops, i.e. improvement of the elemental utilization efficiency in crops improves the seed yield [12].

The availability of silicon in the soil differs depending on the texture, so that a soil with a low level of clay will likely show some silicon deficiency [14]. In a soil with a light texture, the available silicon is washed out from the soil, thereby becoming out of reach to plants. In addition, the rate of silicon uptake by the plant from the soil is usually high. For example, a one ha wheat farm uptakes about 50–150 kg silicon from the soil during the growing season [15]. Due to the reduction of available silicon in intensive agriculture, the application of supplementary silicon fertilizer is required to achieve maximum production [16]. Different values have been reported for the critical concentration of silicon in the soil and plants. For example, the critical threshold of plant's available silicon is from 14 mg/kg soil for extraction with distilled water to 207 mg/kg soil for extraction with 0.005 M sulfuric acid [17]. Additionally, from a physiological point of view, a critical level of the nutrient in the leaf exhibits the minimum nutrient concentration in the cell that allows for the maintenance of metabolic functions [18]. The implications of silicon deficiency in rice were appeared when the silicon concentration in the straw dropped below 10% [19]. In another study on rice, the critical concentration of silicon was reported to be 2.9% [17].

Nanotechnology has had great advances in plant nutrition, and the use of nanofertilizers has attracted much attention due to their excellent properties, such as their quick penetration into the cell membrane. Due to their specific properties, nanoparticles exhibit quite new and different behaviors in comparison with the larger particles of the materials of which they are made [20]. Most nanoparticle atoms are unsaturated and can easily bond with other ions and so they have a significant reactivity [21]. Nano-silicon contains small silicon oxide particles, having the ability to rapidly and easily penetrate into cell membrane. Until now, little attention has been paid to the effects of silicon nanoparticles on the properties of the plant growth medium. Some researchers believe that, in addition to silicic acid, silicon oxide can be directly absorbed from the soil by plants [22]. Regarding the active silicon uptake by wheat [23], this plant can accumulate large amounts of silicon. Since silicon is non-toxic for plants at very high concentrations [24], the application of higher amounts of silicon implies better plant growth [25]. The present study is carried out in order to assess the effects of different silicon sources (potassium silicate and silicon nanoparticles) and levels on wheat efficiency indices in silicon acquisition and utilization.

2 Materials and Methods

The present experiment was carried out in a completely randomized design with two factors and three replications in order to investigate the effects of different levels and sources of silicon on physiological traits and nutrient uptake of seven wheat cultivars in the greenhouse conditions. The treatments used in this study were seven wheat cultivars (*Gonbad, Shiroudi, Shiraz, Mahdavi, Marvdasht, Bahar, and Parsi*) and various soil applications of silicon (control, 200, 400, and 1000 mg/kg as potassium silicate and 50 and 100 mg/kg as nanoparticles) [26]. To ensure the particle size and the purity of the silicon nanoparticles, an electron microscope image and the spectroscopy of particle energy diffraction were prepared at the Razi Matters and Energy Research Institute (Fig. 1).

Firstly, the soil sample was collected from the Research Station for College of Agriculture and Natural Resources, University of Tehran (from depth of 0–30 cm). Based on World Reference Base (WRB), the soil type was *Calcaric Cambisols*. The soil family was Xeric Haplo Cambids, Sandy Loam, Mixed, Active and Thermic. Physical and chemical properties of the soil are analyzed and the results are presented in Table 1. The soil texture was measured by hydrometric method [27], and the field capacity (FC) by pressure plate [28]. Soil pH, electrical conductivity (EC), and cation exchange capacity (CEC) were determined following Bower's method [29], carbon and nitrogen contents according to Walkley-Black [30], calcium carbonate equivalent (CCE) by neutralizing soil carbonates with acid [31], and active calcium carbonate (ACC) by the method of oxalate and titration with potassium permanganate [32], extractable silicon with 0.5 M acetic acid [17], extractable phosphorus with 0.5 M sodium bicarbonate according to Olsen's method, available potassium with normal ammonium acetate extraction and available zinc, copper, manganese, and iron was measured by extraction with DTPA [28].

For the pot experiment, the soil was passed through a 4 mm sieve. Silicon treatments were applied to the pots 8 weeks before planting and maintained for several dry periods. The difference in potassium added through potassium silicate was calculated and adjusted by potassium sulfate. According to the results of a soil test, urea, iron chelate, and zinc sulfate were applied at optimal rates in order to eliminate nitrogen, iron, and zinc deficiencies [33]. Seeds of 7 wheat cultivars were provided from Seed and Plant Improvement Institute, Karaj. The seeds were disinfected and then planted in 3 kg plastic pots. One week later, the seedlings were thinned to 6 per pot. The pots were irrigated with distilled water during the growing period up to about 70% of the field capacity, by weighing the pots. Eight weeks after germination, the plants were harvested, washed with distilled water and then dried in an oven at 70 °C for 48 h.

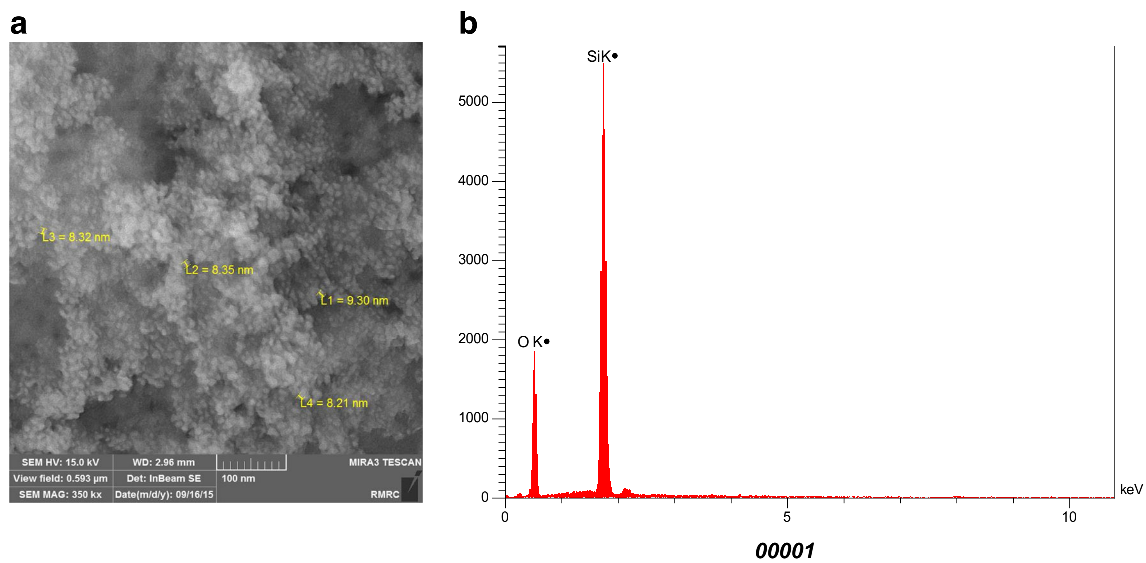

Fig. 1 **a** Scanning electron microscopy (SEM) and **b** energy dispersive x-ray spectroscopy (EDS) of Silicon nanoparticles

Shoot dry weight (SDW) and root dry weight (RDW) were recorded, and then the plant materials were ground for further analysis. In order to calculate the shoot silicon concentration (SSC) and root silicon concentration (SSC), the materials were dyed with amino molybdenum blue. After the preparation of an extract from the desired sample, according to Elliott and Snyder [34], the silicon concentration was determined using a spectrophotometer device (Schimadzo UV-3100) at a wavelength of 650 nm. Total shoot silicon (TSS) was calculated by multiplying the silicon concentration by the shoot dry weight. Other efficiency indices including shoot silicon efficiency (SSE), silicon acquisition efficiency (SACE), silicon utilization efficiency (SUTE), calculated silicon efficiency (CSE), and silicon utilization index (SUI) were calculated as follows [35]:

(1) $\mathrm{SSE} = [SDW(-Si)/SDW(+Si)]$
(2) $SACE = [TS(-Si)/TS(+Si)]$
(3) $SUTE = [SDW/TSS]$
(4) $\mathrm{CSE} = [SACE \times SUTE]$
(5) $SUI = [SDW/SSC]$

–Si = the dry matter produced in the control treatment; +Si = the silicon treatments (at various levels and from different sources).

The results were statistically analyzed by using SAS software, and the means were compared using Duncan's multiple range test ($P < 0.01$).

3 Results and Discussion

The results of physical and chemical analysis of the soil are presented in Table 1. According to the table, this soil with light texture and with silicon content less than the critical level (only 54 mg of silicon can be extracted with 0.5 M acetic acid per kg of soil) was ideal for this experiment and had no specific limitations. Its texture was also suitable for wheat cultivation [17]. Moreover, the results presented in Fig. 1 showed that the silicon particles are nano-sized, so they can be absorbed by the plant [22].

The results of variance analysis for all studied traits and indices are shown in Table 2. The results show that silicon application, wheat cultivar, and their interaction had ($P < 0.01$) significant effects on root and shoot dry weights, root and shoot silicon concentrations, total shoot silicon, and all efficiency indices including shoot silicon efficiency, silicon utilization efficiency, silicon acquisition efficiency, calculated silicon efficiency, and silicon utilization index .

Table 1 Important physical and chemical properties of the experimental soil

Soil textural class	Sand	Silt	Clay	FC	pH	EC	CEC	CCE	ACC	C Organic	N	K Absorbable	P	Si	Fe DTPA extractable	Cu	Mn	Zn
	g/100 g				–	dS /m	cmolc/kg	g/100 g							mg/kg			
Sandy loam	59	24	17	21.43	8.5	2.31	15.06	11.83	4	0.79	0.09	89.3	18.2	20.16	3.12	1.02	7.6	0.6

Table 2 Variance analysis of the effects of wheat cultivars and different silicon levels and sources on the traits studied

Sources of change	DF	Mean squares									
		SDW	RDW	RSC	SSC	TSS	SSE	SACE	SUTE	CSE	SUI
Sources of silicon	5	1.473**	0.113**	0.032**	0.371**	237.4**	1970.0**	10,391.7**	0.053**	1549.3**	0.222**
Wheat cultivars	6	1.603**	0.804**	0.283**	0.013**	49.94**	6259.3**	4997.1**	0.006**	170.8**	0.097**
Sources of silicon * Wheat cultivars	30	0.259**	0.140**	0.069**	0.007**	11.71**	611.8**	673.1**	0.003**	103.5**	0.020**
Error	84	0.092	0.035	0.0008	0.0009	2.699	303.0	209.3	0.0002	15.2	0.006
Coefficient of variation		13.5	20.8	8.91	5.91	14.02	17.91	17.95	7.43	22.04	16.64

* and ** in each column indicate significance at 0.05 and 0.01, respectively

3.1 Plant Yield Response

The main and interactive effects of different silicon administrations and wheat cultivars on plant yields, including shoot and root dry weights, as well as the ratio of root dry weight to shoot dry weight are presented in Table 3.

According to the results in Table 3 (a), the application of different treatments of silicon had a significant effect on the dry weights of the wheat cultivars, so that the shoot dry weight ranged from 1.19 to 3.2 g. However, *Gonbad* cultivar (3.2 g) recoded the highest shoot dry weight, while the lowest was achieved by *Marvdasht* cultivar (1.19 g) (Table 3a). According to Table 3 (a), shoot dry weight showed differences between control plants and those treated with 1000 mg/kg potassium silicate or 100 mg/kg silicon nanoparticles. These results are quite logical due to the role of silicon in the production of biomass by improving the availability of other elements for the plants and alleviating the deficiency of other nutrients [36]. Furthermore, the effect of nano-silicon is due to its nanoparticle size compared to other silicon sources.

Table 3 Comparison of the main and interactive effects on growth parameters

Wheat cultivars	Sources of silicon: Control		Potassium silicate 200		Potassium silicate 400		Potassium silicate 1000		Nano-silica 50		Nano-silica 100		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Total mean
a) Shoot Dry weight (SDW) (gr in pot)													
Gonbad	2.29c-l	0.27	2.35c-k	0.42	2.54b-h	0.08	3.06ab	0.38	2.52b-i	0.34	2.74a-e	0.23	2.58A
Shiroudi	1.68lmn	0.09	1.68lmn	0.05	1.90j-m	0.31	3.02ab	0.15	2.03f-l	0.00	2.25d-l	0.07	2.09D
Shiraz	1.74klm	0.25	2.15e-l	0.36	2.55b-h	0.36	2.95ab	0.25	1.99 h-l	0.06	2.76a-d	0.14	2.35 BC
Mahdavi	2.49b-j	0.05	2.15e-l	0.23	2.22d-l	0.04	2.61b-g	0.37	2.09f-l	0.17	2.63a-f	0.18	2.36 BC
Marvdasht	2.02 g-l	0.17	1.75klm	0.30	1.19n	0.13	2.01 g-l	0.07	1.37mn	0.11	1.75klm	0.06	1.68E
Bahar	1.93i-m	0.65	2.33c-k	0.24	2.28c-l	0.13	3.20a	0.34	2.23d-l	0.22	2.85abc	0.39	2.47AB
Parsi	2.48b-j	0.27	2.01 g-l	0.13	2.03f-l	0.21	2.19d-l	0.16	2.52b-i	0.29	1.91j-m	0.11	2.19CD
Total mean	2.09C		2.06C		2.10C		2.72A		2.01C		2.41B		
b) Root Dry weight (RDW) (gr in pot)													
Gonbad	0.98c-k	0.11	0.97c-l	0.06	1.25a-d	0.19	0.96c-m	0.02	0.71 h-r	0.01	1.25abc	0.04	1.02B
Shiroudi	0.87e-n	0.12	0.60 l-r	0.12	0.91c-n	0.23	1.00c-j	0.08	1.02c-j	0.17	0.95c-n	0.06	0.89 BC
Shiraz	0.65j-r	0.00	0.97c-l	0.11	1.24a-e	0.33	0.78 g-p	0.15	0.79 g-p	0.07	1.06b-h	0.15	0.91 BC
Mahdavi	1.16b-f	0.06	0.88d-n	0.02	1.39ab	0.34	1.02c-j	0.10	0.99c-j	0.14	1.52a	0.28	1.15A
Marvdasht	0.59 m-r	0.08	0.49o-r	0.06	0.37r	0.06	0.58n-r	0.03	0.41qr	0.08	0.43pqr	0.16	0.47D
Bahar	1.14b-g	0.45	0.61 k-r	0.04	0.94c-n	0.21	0.68i-r	0.13	0.74 h-q	0.04	0.88d-n	0.04	0.83C
Parsi	0.68i-r	0.04	1.55a	0.18	0.84f-o	0.13	0.89c-n	0.17	1.04b-i	0.04	0.78 g-p	0.06	0.96 BC
Total mean	0.86AB		0.86AB		0.98A		0.84B		0.81B		0.98A		

The capital letters in the table show the results of the comparison of the means for the main effects at a significance level of 0.05 and the lower-case letters show the results of the comparison of the means for interactive effects at a significance level of 0.05. At least one same letter indicates an insignificant difference between treatments

Roots are important organs to absorb water and nutrients, and their biomass is the result of many ecological and agricultural factors and reflects the fertility of the underlying soil [37]. The results of Table 3(b) indicate the significant effects of different silicon treatments on root growth. The root dry weight ranged from 0.37 to 1.55 g. Maximum root dry weight was recorded for *Mahdavi* cultivar (1.55 g), while the minimum was obtained by *Marvdasht* cultivar (0.37 g) (Table 3b). However, root dry weight did not show any significant differences among the treatments (Table 3b). The effect of silicon on root growth is mixed, and there are some reports on the positive effects of silicon on root dry weight [38, 39]. The root morphology is an important factor in the efficient acquisition of silicon and other nutrients and water uptake, thereby in the adaptability of plants to the deficiencies of water and nutrients. Increased root volume or its absorbing surface, increased root exudates, and increased root weight or length may improve nutrient uptake [40].

3.2 Silicon Concentration and Acquisition

The main and interactive effects of different silicon levels and sources and wheat cultivars on the average concentration of silicon in root (a) and shoot (b), and the shoot silicon acquisition (c) are displayed in Table 4.

The capital letters in the table show the main effects at $P < 0.05$, and the lower-case letters show the interactive effects at $P < 0.05$. At least one same letter indicates an insignificant difference between the values. Silicon treatments had significant effects on the silicon concentration in the roots and shoot of wheat cultivars, so that their content in the root ranged from 0.74 to 1.75% and in the shoot from 0.29 to 0.77% (Table 4a and b). A substantial variability in the nutrient concentrations in the growth medium slightly changes the nutrient concentrations in the plant tissue. Therefore, it can be concluded that the concentrations of most nutrients in plant tissues are limited to relatively narrow domains [12]. Additionally, reduction of the nutrient concentrations in the plant tissues is related to ageing, which is related to the increased yield of dry matter in the plant and is known as the effect of dilution, confirms the results of other studies. With regard to the non-usefulness of element concentration in plants, it is served as a parameter for diagnosis of genotype resistance to nutrient deficiency. In fact, the total shoot silicon shows the difference between the genotypes better than the silicon acquisition [41]. Therefore, the results showed significant differences in the ability of the wheat cultivars in silicon accumulation, in both silicon treatments and control treatment. In this study, the total shoot silicon ranged between 4.82 and 19.13 mg/kg (Table 4c).

The silicon concentration and total silicon acquisition in the shoot increased with the application of silicon. Application of potassium silicate at 1000 mg/kg soil (49.9% and 13.57 mg/kg in the pot) showed a significant increase in these traits as compared to lower levels and the control treatment, albeit showing a less significant increase in comparison with the various levels of the silicon nanoparticles, which is acceptable considering the possibility of faster and easier absorption of the nanoparticles (Table 4b and c). The above conclusion is on the basis of the increase in the silicon concentration in the shoot and consequently the increase in the total silicon as a result of increased silicon concentration in the soil solution following the application of silicon, which is in agreement with the findings of other studies [38]. According to Table 4(c), Shiraz cultivar obtained the maximum total silicon (13.19 mg in the pot), which the minimum value was recorded for *Marvdasht* cultivar (8.58 mg in the pot).

3.3 Silicon Efficiency Indices

The main and interactive effects of different levels and sources of silicon and wheat cultivars on the average silicon acquisition efficiency indices, including shoot silicon efficiency (a), silicon acquisition efficiency (b), silicon utilization efficiency or internal silicon utilization efficiency (c), calculated silicon efficiency (d), and silicon utilization efficiency (e) are presented in Table 5. According to this table, application of silicon had a significant effect on all efficiency indices in wheat cultivars.

In this study, a wide range of disorders was observed in the plants in response to the application of silicon. The values for shoot silicon efficiency are presented in Table 5a. Accordingly, the shoot silicon efficiency of wheat cultivars at different levels of silicon varied from 55.94 to 170.78. Considering the statistical significance between shoot dry weights, *Marvdasht* and *Parsi* were selected as silicon-efficient cultivars, while *Shiroudi*, *Bahar*, and *Shiraz* were selected as silicon-inefficient cultivars. The underlying mechanisms for the different shoot silicon efficiency of plants are yet to be fully understood; However, according to the literature, it is believed that the plant response to the application of silicon and the production of dry matter is different in various plants [36, 42]. Generally, shoot efficiency in a specific genotype can be determined by such mechanisms as high uptake of the element by the root, silicon transportation to the shoot, and its physiological efficiency (utilization efficiency) [43].

According to the correlation values in Table 6, the significant relationship between shoot silicon and total absorbed silicon (−0.49) or shoot dry weight (−0.7) showed that by increasing the silicon efficiency, the silicon acquisition and the dry matter production decreased. The silicon-efficient wheat cultivars had a less level of shoot silicon compared to the inefficient cultivars. Specifically, *Marvdasht* cultivar with the highest level of silicon efficiency (125.43%) had the lowest total shoot silicon (8.58%), while *Shiraz* with the least shoot silicon efficiency (76.80%) had the highest total shoot

Table 4 Comparison of the main and interactive effects on silicon indices

Sources of silicon													
Wheat cultivars	Control		Potassium silicate 200		Potassium silicate 400		Potassium silicate 1000		Nano-silica 50		Nano-silica 100		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Total mean
a) Root Silicon Concentrations (RSC)													
Gonbad	0.82 m-r	0.08	0.84 l-r	0.01	0.91i-r	0.04	0.89j-r	0.01	0.93i-r	0.02	0.99f-n	0.08	0.89D
Shiroudi	0.97 g-o	0.03	1.35b	0.12	0.95 h-p	0.04	0.79o-r	0.03	1.04d-k	0.03	0.95 h-o	0.09	1.0 BC
Shiraz	0.76qr	0.05	1.18cde	0.04	1.00f-l	0.04	0.74r	0.04	0.97 g-n	0.05	1.08d-j	0.02	0.95CD
Mahdavi	0.91i-r	0.04	0.94 h-p	0.05	1.12c-h	0.09	0.77pqr	0.05	1.01e-l	0.04	1.08d-i	0.03	0.97CD
Marvdasht	0.90i-r	0.06	1.16c-f	0.09	1.20bcd	0.10	1.01e-l	0.06	1.75a	0.20	1.68a	0.21	1.28A
Bahar	0.85 l-r	0.08	1.11c-h	0.09	1.01e-l	0.00	1.05d-k	0.08	1.28bc	0.07	0.99f-m	0.04	1.05B
Parsi	0.90i-r	0.10	1.14c-g	0.05	0.81n-r	0.07	0.88 k-r	0.02	1.07d-j	0.09	1.05d-k	0.03	0.97C
Total mean	0.87C		1.01A		1.0B		0.87C		1.14A		1.11A		
b) Shoot Silicon Concentrations (SSC)													
Gonbad	0.39nop	0.03	0.29r	0.01	0.37pq	0.04	0.47i-l	0.04	0.76a	0.00	0.68bcd	0.01	0.49C
Shiroudi	0.32qr	0.01	0.29r	0.01	0.50 h-k	0.04	0.43 l-p	0.02	0.77a	0.01	0.64cde	0.01	0.48C
Shiraz	0.48i-l	0.01	0.51ghi	0.04	0.44 k-o	0.00	0.56 fg	0.03	0.74a	0.01	0.64cde	0.01	0.56A
Mahdavi	0.47i-l	0.05	0.45j-m	0.05	0.45i-l	0.01	0.51ghi	0.02	0.73ab	0.01	0.62de	0.01	0.53B
Marvdasht	0.39nop	0.01	0.43 l-p	0.04	0.46i-l	0.02	0.49 h-k	0.01	0.73ab	0.01	0.63cde	0.03	0.53B
Bahar	0.32qr	0.03	0.39 m-p	0.00	0.44 k-o	0.02	0.54gh	0.05	0.69bc	0.02	0.60ef	0.01	0.49C
Parsi	0.44 k-o	0.04	0.49 h-k	0.03	0.44 k-n	0.02	0.50 g-j	0.02	0.68bcd	0.01	0.62de	0.01	0.52B
Total mean	0.4E		0.4E		0.44D		0.49C		0.72A		0.63B		
c) Total Shoot Silicon (TSS)													
Gonbad	8.85j-n	0.44	6.90 m-p	1.29	9.51j-n	1.05	14.35d-g	2.03	19.13a	2.56	18.56ab	1.69	12.88A
Shiroudi	5.46op	0.39	4.82p	0.10	9.56j-n	2.38	12.92e-i	1.20	15.56b-e	0.16	14.37d-g	0.34	10.44C
Shiraz	8.35 k-o	1.15	10.85 h-l	1.70	11.15 h-k	1.54	16.41a-d	1.37	14.76c-f	0.61	17.64abc	1.04	13.19A
Mahdavi	11.68 g-j	1.31	9.66j-m	1.58	10.06i-m	0.12	13.28e-h	1.37	15.16cde	1.01	16.42a-d	0.94	12.88AB
Marvdasht	7.79 l-p	0.56	7.46 m-p	1.07	5.42op	0.67	9.85i-m	0.39	9.95i-m	0.92	11.08 h-k	0.67	8.58D
Bahar	6.43nop	2.71	9.15j-n	0.88	10.05i-m	0.63	17.19a-d	2.34	15.33cde	1.23	17.24a-d	2.31	12.56AB
Parsi	10.93 h-l	1.01	9.85i-m	1.10	9.06j-n	1.33	11.05 h-k	1.23	17.03a-d	1.79	11.86f-j	0.89	11.63B
Total mean	8.49C		8.38C		9.25C		13.57C		15.27A		15.30A		

The capital letters in the table show the results of the comparison of the means for the main effects at a significance level of 0.05 and the lower-case letters show the results of the comparison of the means for interactive effects at a significance level of 0.05. At least one same letter indicates an insignificant difference between treatments

silicon (13.19%). Additionally, *Marvdasht* and *Shiraz* cultivars had the highest (1.28%) and the lowest (0.59%) values in the root, respectively. In addition, regarding the dry matter production, *Marvdasht* cultivar had the minimum values for shoot and root dry weights. Nevertheless, researchers reported that a higher total acquisition of the element and its utilization, along with a greater allocation of it to the production of dry matter, is characteristic of efficient genotypes in deficiency conditions [44], but the results of the present study are inconsistent, except for the root silicon concentration. Therefore, a simultaneous attention to the acquisition mechanism, distribution, and utilization of the nutrients may provide a better understanding of the efficiency of the cultivars. The acquisition of nutrients by crops at a sufficient ration is of great importance to produce higher yields. Accordingly, the distribution of nutrients accumulated in the shoots and seeds is associated with an improved crop yield [12]. There are many reports indicating a difference in the utilization factor due to increased acquisition efficiency from the soil nutrients or increased utilization efficiency by the plant [45]. Although this important issue has not been extensively studied for silicon, it seems that SACE and SUTE in the plant tissues and cells are important factors in the silicon efficiency of the cereals [46]. The results showed that the average silicon utilization efficiency and silicon acquisition efficiency of wheat cultivars at various levels of silicon have been reported to be from 35.10 to 144.72 (Table 5b) and 0.13 to 0.35, respectively (Table 5c). The noteworthy point in this regard is the increased silicon utilization efficiency and reduced silicon acquisition efficiency; so that the *Parsi*, *Marvdasht*, and *Mahdavi* cultivars with the highest average silicon utilization efficiency had the least silicon acquisition efficiency. In addition, according to the results of the average silicon utilization efficiency and silicon acquisition efficiency among different silicon levels and sources, it was found that the above indices decreased with increasing silicon treatments. Thus, the minimum silicon utilization and acquisition efficiencies among potassium silicate levels was attributed to 1000 mg potassium silicate per kg soil (66.30 and 0.2, respectively) and among the silicon nanoparticles to 50 mg nano-silicon per kg soil (57.59 and 0.13, respectively), which were not statistically different from that value recorded for the level of 100 mg nano-silicon per kg

Table 5 Comparison of the main and interactive effects on silicon efficiencies

Sources of silicon													
Wheat cultivars	Control		Potassium silicate 200		Potassium silicate 400		Potassium silicate 1000		Nano-silica 50		Nano-silica 100		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Total mean
a) Shoot Silicon Efficiency (SSE)													
Gonbad	–	–	98.67c-h	6.11	89.85d-k	8.15	75.07 h-k	6.47	92.72d-g	16.69	84.21f-k	12.50	90.08C
Shiroudi	–	–	100.34c-h	7.59	90.95d-j	16.84	55.94 k	5.55	82.78f-k	4.22	75.01 h-k	6.15	84.17CD
Shiraz	–	–	81.51 g-k	2.60	68.98 h-k	10.61	59.25jk	7.90	87.36ek	10.44	63.76ijk	11.96	76.80D
Mahdavi	–	–	117.22b-f	13.60	112.24c-g	4.27	97.37c-i	13.96	119.99b-e	10.66	95.16d-i	8.46	106.99B
Marvdasht	–	–	117.73b-f	18.07	170.78a	13.47	100.89c-h	11.55	147.94ab	12.36	115.28b-g	8.41	125.43A
Bahar	–	–	85.10e-k	31.38	84.21f-k	25.38	63.30ijk	28.13	90.13b-k	38.09	68.08 h-k	23.79	81.80CD
Parsi	–	–	123.23bcd	12.04	122.58bcd	12.23	113.68c-g	12.58	100.45c-h	19.81	130.59bc	17.69	115.08AB
Total mean	–		103.4A		105.65A		80.78C		103.05A		90.29 BC		
b) Silicon Acquisition Efficiency (SACE)													
Gonbad	–	–	131.83ab	19.14	94.47c-h	13.73	62.46j-q	5.81	47.28n-q	7.99	48.20 m-q	6.01	80.70B
Shiroudi	–	–	113.25bcd	7.84	60.15 k-q	13.27	42.94opq	7.18	35.10q	2.47	38.08pq	3.56	64.91C
Shiraz	–	–	77.41f-l	6.95	75.72f-m	11.34	50.70 l-q	3.47	56.39 k-q	5.75	47.82 m-q	8.74	68.00C
Mahdavi	–	–	122.04abc	6.81	116.24bcd	14.03	88.62d-j	12.27	76.82f-l	4.29	71.56 g-n	10.64	95.87A
Marvdasht	–	–	107.13b-e	19.87	144.72a	9.11	79.34e-k	8.59	78.76e-l	7.70	70.26 h-o	1.16	96.70A
Bahar	–	–	71.88 g-n	31.38	64.05j-p	25.84	39.36pq	20.99	43.69n-q	21.91	37.80pq	17.27	59.46C
Parsi	–	–	111.36bcd	5.64	121.60abc	6.43	100.73c-f	17.74	65.09i-p	10.44	92.43d-i	7.75	98.53A
Total mean	–		104.98A		96.70A		66.30B		57.59B		58.01B		
c) Silicon Utilization Efficiency (SUTE)													
Gonbad	0.26 cd	0.02	0.34a	0.01	0.27c	0.03	0.21f-j	0.02	0.13op	0.00	0.15nop	0.00	0.22A
Shiroudi	0.31b	0.01	0.35a	0.02	0.20 g-k	0.02	0.24def	0.01	0.13p	0.00	0.16 m-p	0.00	0.23A
Shiraz	0.21f-k	0.00	0.20 h-k	0.02	0.23efg	0.00	0.18klm	0.01	0.13op	0.00	0.16 m-p	0.00	0.18D
Mahdavi	0.22f-j	0.02	0.23fgh	0.02	0.22f-i	0.01	0.20i-k	0.01	0.14nop	0.00	0.16 l-p	0.00	0.19CD
Marvdasht	0.26 cd	0.00	0.24def	0.02	0.22f-i	0.01	0.20 g-k	0.00	0.14nop	0.00	0.16 m-p	0.01	0.20C
Bahar	0.31b	0.03	0.25cde	0.00	0.23e-i	0.01	0.19j-k	0.02	0.15nop	0.00	0.17lmn	0.00	0.21B
Parsi	0.23e-h	0.02	0.21f-k	0.01	0.23f-i	0.01	0.20 h-k	0.01	0.15nop	0.00	0.16 l-o	0.00	0.19CD
Total mean	0.25A		0.25A		0.22B		0.20C		0.13E		0.15D		
d) Calculated Silicon Efficiency (CSE)													
Gonbad	25.81bc	1.81	45.10a	7.53	25.97bc	6.58	13.45 h-n	1.97	6.23no	1.05	7.14mno	0.95	20.61A
Shiroudi	30.88b	0.97	39.51a	3.08	12.41i-n	3.54	10.17j-o	2.16	4.59o	0.33	5.96o	0.50	17.25B
Shiraz	20.85c-h	0.30	15.44f-k	2.68	17.32e-j	2.46	9.09 k-o	0.29	7.60 l-o	0.71	7.49 l-o	1.38	12.96C
Mahdavi	21.59c-g	2.49	27.70bc	4.21	25.67bc	3.25	17.33e-j	2.34	10.59j-o	0.72	11.46i-o	1.65	19.05AB
Marvdasht	25.93bc	0.44	25.41bcd	5.73	31.90b	2.87	16.20e-k	1.87	10.87i-o	1.15	11.14i-o	0.57	20.24A
Bahar	31.09b	2.69	18.27d-i	7.90	14.73 g-m	6.33	7.31 l-o	3.88	6.32no	3.11	6.28no	2.92	13.99C
Parsi	22.73c-f	2.00	22.95cde	2.36	27.49bc	2.60	20.17c-h	4.37	9.65 k-o	1.64	14.91 g-l	1.33	19.65AB
Total mean	25.55A		27.76A		22.21B		13.38C		7.97D		9.19D		
e) Silicon Utilization Index (SUI)													
Gonbad	0.60bcd	0.11	0.80a	0.14	0.69ab	0.07	0.66bc	0.09	0.33 k-q	0.04	0.41f-p	0.03	0.57A
Shiroudi	0.52c-h	0.03	0.59bcd	0.05	0.38 g-p	0.04	0.71ab	0.01	0.27opq	0.00	0.35j-p	0.02	0.46 BC
Shiraz	0.36i-p	0.05	0.43e-n	0.09	0.58bcd	0.08	0.53c-g	0.06	0.27opq	0.00	0.43e-m	0.02	0.43C
Mahdavi	0.54c-f	0.06	0.48d-j	0.07	0.49d-g	0.02	0.51c-i	0.09	0.29 m-q	0.03	0.42e-n	0.03	0.45C
Marvdasht	0.52c-h	0.05	0.42e-o	0.10	0.26pq	0.03	0.41f-p	0.01	0.19q	0.01	0.28n-q	0.02	0.34D
Bahar	0.59bcd	0.15	0.60bcd	0.07	0.52c-h	0.04	0.60bcd	0.10	0.33 k-q	0.04	0.47d-k	0.07	0.51B
Parsi	0.57b-e	0.09	0.41f-p	0.01	0.46d-l	0.03	0.43e-m	0.02	0.37 h-p	0.05	0.31 l-q	0.01	0.42C
Total mean	0.52AB		0.53AB		0.48B		0.55A		0.29D		0.38C		

The capital letters in the table show the results of the comparison of the means for the main effects at a significance level of 0.05 and the lower-case letters show the results of the comparison of the means for interactive effects at a significance level of 0.05. At least one same letter indicates an insignificant difference between treatments

Table 6 Correlation between the studied parameters

	SDW	RDW	RSC	SSC	TSS	SSE	SACE	SUTE	CSE	SUI
SDW	1									
RDW	0.41**	1								
RSC	−0.37**	−0.28**	1							
SSC	0.08 ns	−0.02 ns	0.27**	1						
TSS	0.70**	0.25**	−0.07 ns	0.75**	1					
SSE	−0.70**	−0.27**	0.31**	−0.03 ns	−0.49**	1				
SACE	−0.52**	−0.08 ns	−0.03 ns	−0.60**	−0.76**	0.72**	1			
SUTE	−0.14 ns	−0.01 ns	−0.21*	−0.96**	−0.76**	0.04 ns	0.58**	1		
CSE	−0.40**	−0.06 ns	−0.11 ns	−0.81**	−0.82**	0.46**	0.90**	0.86**	1	
SUI	0.60**	0.28**	−0.41**	−0.71**	−0.14 ns	−0.44**	0.12 ns	0.69**	0.40**	1

* and ** in each column indicate the significant level of 5 and 1%, respectively

soil. Moreover, the application of silicon nanoparticles in comparison with the potassium silicate exhibited lower silicon utilization and acquisition efficiencies. The results of this study show that there is a genotype-mediated difference in terms of silicon utilization and acquisition efficiencies.

The data in Table 6 show a significant negative relationship between silicon utilization & acquisition efficiencies and the silicon concentration in the shoot (−0.6 and −0.96), the total shoot silicon (−0.76 and −0.58). Averagely, the utilization and acquisition efficiencies of the element is high at lower levels of the element, being decreased at higher levels of the element. This means that the plant has not been able to uptake the element under excessive utilization conditions, which is due to the saturation of its acquisition mechanisms [47]. The results also showed a significant relationship between shoot silicon efficiency and silicon acquisition efficiency (0.72). The calculated silicon efficiency index (CSE) is also obtained by multiplying the silicon acquisition efficiency by its utilization efficiency. The data in Table 5d show that the calculated silicon efficiency of wheat cultivars is different depending on the silicon level. The average calculated silicon efficiency of wheat cultivars at different levels of silicon ranged from 4.59 to 45.1 (Table 5d), but the average calculated silicon efficiency among the cultivars ranged from 20.61 for *Gonbad* cultivar to 12.96 for *Shiraz* cultivar. The average calculated silicon efficiency among the different silicon levels and sources indicates a reduction in the above index at higher levels of silicon compared to the control treatment. In addition, the use of silicon nanoparticles showed a significant decrease compared to the use of potassium silicate. It should be noted that the cultivars with the highest shoot silicon efficiency (*Marvdasht* and *Parsi*) were classified in the first group of average calculated silicon efficiency (*Gonbad*, *Marvdasht*, *Parsi*, and *Mahdavi*). This case also holds true for cultivars with the lowest shoot silicon efficiency, including Bahar and Shiraz, which had the least average values for both indices.

The correlation values in Table 6 indicate that there is a significant relationship between shoot silicon efficiency and calculated silicon efficiency (0.46). Accordingly, by increasing the shoot silicon efficiency in the wheat cultivars, the calculated silicon efficiency is increased, which is obtained by multiplying the silicon acquisition efficiency by its utilization efficiency.

The utilization efficiency can be defined as the maximum economic yield produced per unit of the element utilized or adsorbed by the plant. The silicon utilization index (SUI), similar to the silicon utilization efficiency index (SUTE), is proportional to the internal silicon utilization efficiency, with the difference that this parameter is obtained by dividing the dry weight by the silicon concentration, instead of the total shoot silicon. In this research, the results of the estimation of these two indices are different. The results of the average utilization index of wheat cultivars at different silicon levels and sources are presented in Table 5e.The average index increased from 0.19 to 0.8. The average silicon utilization index among the different cultivars ranged from 0.57 for *Gonbad* cultivar to 0.34 for *Marvdasht* cultivar. However, different results were obtained for its average among the silicon levels and sources compared to other indices. Thus, increasing the level of potassium silicate application left no significant differences from the zero application (control), but it was still higher in plants treated with silicon nanoparticles than those treated with potassium silicate. High efficiency in internal utilization of the element depends on the root acquisition capacity of the element in order to provide high growth rates when it is low in the plant tissues [44].

4 Conclusion

The application of silicon had a significant effect on the morpho-physiological traits and the silicon acquisition/utilization efficiency relationships. Furthermore, there was a significant relationship ($p \leq 0.01$) between the shoot silicon efficiency and the silicon acquisition efficiency (0.72). *Marvdasht* and *Parsi* cultivars were the most effective in terms of shoot silicon efficiency. In general, by selecting and identifying the silicon-efficient cultivars of a plant, it is possible to identify genes responsible for silicon efficiency, and it will be possible to develop cultivars to successfully cultivate in soils having silicon efficiency, especially in calcareous soils. The selection and modification of silicon-efficient wheat cultivars can be a successful and promising strategy to maintain production in low-input and environmental friendly agricultural systems.

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