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Research Article

Effect of Silicon Sulphate and Silicic Acid Rates on Yield and Quality of Wheat (*Triticum aestivum* L.)

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ABSTRACT

The utilization of silicon (Si) sources is a crucial agricultural tool that requires optimization to promote sustainable practices. The application of Si provides the implementation of biological mechanisms of plant nutrition, growth promotion, and protection. The objectives of this experiment were to investigate the relative efficacy of Si sources and levels on the growth and yield of wheat. The study examined the effects of silicon sulphate and silicic acid levels on growth, spike characteristics, yield parameters, and macro- and micronutrient concentrations of wheat during the 2-season. The entire above-indicated parameters were significantly ($p < 0.05$) increased with increasing levels of silicon sulphate and silicic acid compared to the control. Foliar applications of silicon sulphate 150 ppm and silicic acid 60 ppm statistically ($p < 0.05$) enhanced grain N concentration and the grain yield by 136.14 and 77.85%, 43.49 and 34.52% in the 1st season, and by 78.62 and 54.40%, 43.53 and 33.18% in the 2nd season, respectively, as compared with control. Overall, foliar applications of silicon sulphate at 150 ppm and silicic acid at 60 ppm were greatly efficient amongst all Si levels and sources in improving growth and spike characters, increasing yield parameters, and elevating grain nutrients. Finally, the treatment of silicon sulfate at 150 ppm was more effective than the treatment of silicic acid at 60 ppm in increasing growth, grain nutrients, and productivity of wheat and attaining agricultural sustainability under experiment conditions.

Keywords: Grain nutrients, Silicon sulphate, Silicic acid, Wheat.

INTRODUCTION

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops throughout the world and largely responds to fertilizer-adding. Universally, the crop of wheat is considered the major- most important vegetable protein source in the human diet, which contains a higher content of protein compared to other cereal crops like barley, maize, sorghum, and rice [1]. For future food security and to ensure social stability, the increase in wheat production should equilibrium with the food demand and population increase [2, 3]. In Egypt, wheat is the main important cereal crop followed by maize and rice, and the first-most important crop in total production. In Egypt, the wheat cultivated area was estimated about 3.42 million feddan and it yielded approximately 9.70 million tons year^{-1} [4]. Silicon (Si) is a major component of most soils and is found in significant concentration in the tissues of crop plants, especially cereal crops [5]. Plants vary widely in the amount of silicon they take up, with some plants excluding it, and others using transporters to move the Si from the soil into their roots. Early plant physiology studies were unable to determine conclusively whether silicon was essential to plant growth, but for some plants, most notably rice, it has proved to be important enough to justify fertilizing Si-deficient fields. Si also improved the water efficiency of drought-stressed plants and affected the concentration of many micro and macro-nutrients in leaf tissue. [6] observed improved water economy and dry matter yield of water by Si application is reported to enhance leaf water potential under water stress conditions. [7, 8] suggested that Si plays an important role in water transport and root growth under drought conditions in sorghum. [9, 10] also reported significant improvement in plant biomass by Si application under drought stress. [11] found that Si is translocated in the form of mono-silicic acid through the xylem in rice. Si can also alleviate imbalances between the zinc and phosphorus supply. Recently several researchers have shown that Si can decrease the toxic effects of aluminium in hydroponics culture in several species [12, 13]. [14] found that Si application significantly increased Si concentration and uptake in wheat plants grown in sand soil. [15] found that Si is closely related to plant growth and yield owing to strengthening the physiological attributes of the maize. [16] pronounced that Si has proved to enhance the photosynthesis process, improve the absorption of nutrients, and increase grain yield in maize. [17] found that Si has been reported to have a significant effect on yield and modify growth in crops. [16] found that the application of Si improved maize grain yield and dry matter accumulation. [18] mentioned that spraying Si as fertilizer is a good fertilization practice for modifying soil quality and attaining optimum yield. [6] observed that silicon increased plant height, leaf area, and dry mass of wheat even under drought. [5, 19] suggested that dry matter and rice yield were increased by spraying Si and some indirect effects of Si also caused an increase in growth and yield in cereals. [20] concluded that there is a high phosphate uptake in rice with Si application which directly correlates with the increased growth and yield. [21] found that spraying Si increased growth and yield due to decreased Na^+ uptake in wheat under salt stress. [22] stated that Si application also influenced the nutrient uptake and accumulation in non-stressed crops. [23] found that Si application influenced the availability of N uptake, which enhances the increase of biomass and prevents N starvation in plants. [24] noticed that the application of Si at the level of 329 kg ha^{-2} with inorganic fertilizer helped in increasing N uptake in rice. [25] demonstrated that Si nutrition promoted N remobilization by stimulating amino acid remobilization from vegetative parts to the grains. [26] suggested that exogenous application of nano-silicon substantially increased the plant height, No. of panicles $plant^{-1}$, No. of grains $panicle^{-1}$, 1000-grain weight, panicle weight, panicle length, and grain yield in diverse rice genotypes, in comparison to untreated plants under drought and well-watered conditions. [27] studied the effect of different concentrations of silica as nanoparticles (NPs) on wheat plants under two irrigation regimes and they found that silica treatment as NPs at 60 ppm concentration significantly increased the plant height, No. of spikes $plant^{-1}$, spike length, seeds $spike^{-1}$, and 1000-seed weight in both irrigation regimes, as compared to the control. [28] evaluated the impact of various concentrations of silicon on oat varieties and they indicated that No. of panicles m^{-2}, kernels $panicle^{-1}$, 1000-kernel weight, grain yield, biological yield, and harvest index were statistically increased with increased silicon concentration as compared to untreated plants. [29] mentioned that foliar application of oligomeric silicic acid greatly increased the rice grain yield by 15 – 45% as compared to the control plot, in India during the 2007-2012 seasons. [30] suggested that plant height, No. of tillers, No. of spikes pot^{-1}, 1000-kernel weight, and grain and straw yield were increased with increasing levels of Nano Silica. [31] remarked that No. of grains $spike^{-1}$, 1000-grain weight, grain yield, biological yield, and harvest index in wheat plants were greatly enhanced with the spraying of Si treatment under soil water conditions. [32] performed the effect of different doses (10, 15, and 20 kg ha^{-1}) of ortho silicic acid granules on rice and they showed that the highest values of plant height, No. of tillers, No. of panicles, panicle weight, grain weight $panicle^{-1}$, 1000-grain weight, and grain yield were recorded at 20 kg ha^{-1} as compared to control. [33] pronounced that the values of spike length, spike weight, and yield were increased by the spraying mono-silicic acid treatment in spring wheat, as compared to control. [34] conducted the impact of 4 concentrations of soluble Si doses, as mono-silicic acid form (0, 15, 30, and 60 kg ha^{-1}) on corn, and they observed that plant height, cob number per plant, and cob yield were dramatically boosted with increasing Si dose as compared to the control. [35] demonstrated that cob length, 100-grain weight, no. of grains cob^{-1}, biological and grain yields, and harvest index were increased by soil application of Si at 100 mg kg^{-1}, relative to the control in both water levels. [36] revealed that the spike length, grains $spike^{-1}$, 1000 grains weight, plant height, grain yield, and biological yield of wheat at various growth stages were markedly increased with increased levels of Si-NPs, as seed priming treatment in both water levels, as compared to the control. Therefore, the current study aimed to examine the relative efficacy of Si sources (silicon sulphate and silicic acid) and levels as foliar application on plant growth, spike characters, yield parameters, and nutrient concentrations in grains of wheat (cv., Misr-1).

MATERIALS AND METHODS

Experimental Site Description:

A field experiment was conducted in two winter growing seasons of 2021/2022 and 2022/2023 in the experimental station of the private farm at Ayat City, Giza Governorate, Egypt to find out the effect of two sources of silicon (silicon sulphate and silicic acid) as fertilizers on growth, yield and quality of wheat cultivar (Misr-1). Three representative soil samples were taken from the experimental site at 0-30 cm depth before planting to analyze physical and chemical characteristics as shown in Table (1).

Table 1. Some physical and chemical properties of soil samples under study area.

Particle size distribution (%)			Texture class	pH (1: 2.5)	EC (dS m^{-1})	Organic Matter (%)	$CaCO_3$ (%)
Sand	*Silt*	*Clay*					
14.24	9.60	73.16	Clay	7.95	0.91	0.82	0.83
Cations (meq l^{-1})				Anions (meq l^{-1})			
Na^+	*K^+*	*Ca^{++}*	*Mg^{++}*	*CO_3^{--}*	*HCO_3^-*	*Cl^-*	*SO_4^{--}*
1.9	0.87	3.57	3.11	0.00	3.09	0.8	4.1
Macronutrient contents (mg $100g^{-1}$)				Micronutrient contents (mg kg^{-1})			
N	*P*	*K*		*Fe*	*Mn*	*Zn*	*Cu*
20.39	3.4	88.3		13.26	8.11	2.06	0.0261

Meteorological Data:

The meteorological data recorded during the growing period of wheat (November to May in both seasons) at the Meteorological Station of Agricultural Research Center, Ministry of Agriculture, Giza, Egypt are presented in Table (2).

Table 2. Mean temperature (C^o), relative humidity (%), and rainfall (mm) at Giza, Egypt during 2021/2022 and 2022/2023 seasons.

Month	Temperature				Relative Humidity		Rainfall	
	1st season		*2nd season*		*1st season*	*2nd season*	*1st season*	*2nd season*
	Max.	Min.	Max.	Min.				
November	28.76	15.98	26.9	16.7	64.16	59.70	0.9	0.3
December	21.6	12.4	24.6	13.9	70.05	64.96	6.7	3.5
January	18.9	9.1	22.9	11.0	68.90	70.42	3.8	3.9
February	21.4	10.2	20.4	10.4	68.44	68.68	8.7	5.6
March	23.4	10.1	27.5	15.9	61.44	54.40	3.8	6.1
April	33.5	16.0	31.0	17.8	45.59	46.90	0.0	1.0
May	35.2	19.0	34.9	20.5	39.47	41.76	0.3	0.0

Experimental Design and Treatments:

All the treatments were laid out in a randomized complete block design (RCBD) with three replications in both seasons (2021/2022 and 2022/2023). Seven foliar treatments were accomplished in this experiment including (1) Ck: 0.00 double distilled water; (2) SS_1: silicon sulphate 50 ppm; (3) SS_2: silicon sulphate 100 ppm; (4) SS_3: silicon sulphate 150 ppm; (5) SA_1: silicic acid 20 ppm; (6) SA_2: silicic acid 40 ppm; (7) SA_3: silicic acid 60 ppm. A winter wheat cultivar Misr-1 was used as plant material, and the grains were obtained from the Agricultural Research Center, Ministry of Agriculture, Giza, Egypt. The experiment site consisted of 21 plots in both growing seasons. The size of each plot was 6 m^2 (3 m length x 2 m wide). Each plot represents one replicate of each treatment, which means 3 plots for each treatment. Wheat grains (cv. Misr-1) were manually drilled in rows and the distance among rows was 20 cm. All agricultural practices were applied to all the plots according to the Ministry of Agriculture

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recommendations. After 45 and 60 days from the sowing date, the wheat plants were sprayed with 0.00 (double distilled water; Ck); 50, 100, and 150 ppm of silicon sulphate (SiS_2, MW = 92.22 g mol^{-1}); 20, 40, and 60 ppm of silicic acid (H_2SiO_3, MW = 78.10 g mol^{-1}). Tween-20 (0.05%) was added with spraying applications as a surfactant at the treatment time.

Measurements and Analysis:

Growth, Yield, and its Attributes

At the harvest stage (plants at 160 days old), growth, spike characters, and yield parameters in terms of plant height (cm), No. of spikes m^{-2}, spike length (cm), grains weight $spike^{-1}$ (g), 1000-grain weight (g), biological yield (ton $fed.^{-1}$), straw yield (ton $fed.^{-1}$), grain yield (ton $fed.^{-1}$) and harvest index (%) were registered. The plant heights were measured at the height from the soil surface to the spike top. The number of spikes m^{-2} was recorded by counting tillers produced spikes in a 1 m × 1 m area of each plot. 1000-grain weight was determined based on the weight of 1000-grain sample from the grain yield of each plot, and counted by an electronic seed counter. Consequently, the grains weight $spike^{-1}$ was determined using an electronic balance. The harvest index (%) was calculated at the ratio of grain yield to the total above-ground biomass yield according to [37].

Soil and Plant Analysis

After the harvesting process, representative grain wheat samples were taken from each plot to measure the macro and micronutrient concentrations in grains such as N, P, and K (%), and Fe, Mn, and Zn (ppm) and determined according to [38, 39]. Soil reaction (pH): Soil pH was determined in (1:2.5) soil water suspension using a pH meter with a glass electrode [38]. EC (dS m^{-1}): was determined in the supernatant solution (1:5) soil water suspension using a digital conductivity bridge [38]. Organic matter (%): was determined by Walkley and Blacks as described by [38]. Particle size distribution: soil was determined by the International Pipette Method as outlined by [40]. Soluble cations (Na, K, Ca, and Mg) and anions (CO_3, HCO_3, CL, and SO_4) were determined in (1:5) soil water extract by [41]. Nitrogen was extracted using KCL. [42]. Phosphorus was extracted using Na_2HCO_3 [43]. Sodium and potassium were determined by flame photometer as described by [38].

Statistical Analyses:

All the data were collected and analyzed by following the analysis of variance (ANOVA) technique according to the One-way Design using the Statistical Software Package MSTAT- c [44]. The least significant differences test (L.S.D) at 5% probability was used to test the significance among mean values of each treatment [45]. Sigma Plot 10.0 (Systat Software Inc., San Jose, CA, USA) was used for the graphical presentation of the data.

RESULTS AND DISCUSSION

Plant Growth and Spike Characters:

Effect of Silicon Sulphate Levels

Results pointed out that various levels of silicon sulphate application statistically ($p < 0.05$) increased the wheat growth and spike characters in terms of plant height, no. of spikes m^{-2}, spike length, grains weight $spike^{-1}$, and 1000-grain weight in comparison to the control treatment in both seasons (Tables 3 and 4). Foliar application of silicon sulphate at 150 ppm concentration to wheat plants substantially enhanced the plant height by 19.79 and 23.08%, No. of spikes m^{-2} by 9.25 and 9.73 %, spike length by 21.57 and 25.82%, grains weight $spike^{-1}$ by 35.20 and 33.80%, and 1000-grain weight by 25.43 and 29.10% in both seasons, respectively, as compared to the values of the control treatment. The obtained findings are in agreement with those by [6] observed that the application of silicon statistically increased plant biomass, plant height, leaf area, and spike weight of wheat even under drought. Similar results were obtained by [15] who registered that the application of silicon (Si) substantially enhanced the leaf area index and plant height of the maize under limited moisture conditions. In addition, [11] illustrated that Si is translocated in the form of mono-silicic acid through the xylem in rice. [16] observed that Si has proved to enhance the photosynthesis process, improve the absorption of nutrients, and increase the plant height and grain yield in

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maize. These results were in harmony with the study of [26, 27, 28] who also indicated that the application of Si markedly enhanced plant growth and spike characters in different cereal crops.

Effect of Silicic Acid Levels

The evaluated wheat growth and spike characters were significantly ($p < 0.05$) influenced by foliar application of silicic acid with different levels as compared to the control treatment in both seasons (Tables 3 and 4). Foliar application of silicic acid at 60 ppm concentration to wheat plants statistically enhanced the plant height, No. of spikes m^{-2}, spike length, grains weight $spike^{-1}$, and 1000-grain weight as compared to the control in both seasons. In comparison to the control, treatment of silicic acid at 60 ppm concentration significantly increased plant height by 13.89 and 14.05 %, No. of spikes m^{-2} by 5.81 and 6.08%, spike length by 17.09 and 20.78%, grains weight $spike^{-1}$ by 25.56 and 17.89%, and 1000-grain weight by 17.51 and 16.39% in both seasons, respectively. Overall, results demonstrated that the highest values of wheat growth and spike characters were recorded from the plants treated with silicon sulphate at 150 ppm followed by silicic acid at 60 ppm treatment, and the lowest values of previous parameters were registered from the plants treated with silicic acid at 20 ppm followed by silicon sulphate at 50 ppm treatment in both seasons, respectively, as compared to the values of the control treatment. These results may be due to the high content of silicic acid as foliar application caused an increase in grain yield and quality of wheat. Such results are in harmony with those obtained by [17, 46] who found that Si has been reported to have a significant effect on growth in crops. Moreover, [6] observed that silicon increased straw yield and weight of 1000 grains of wheat even under drought. Similarly, [19] showed that the application of silicon markedly increased the plant height, dry matter, and yield in rice. [18] mentioned the application of silicon as fertilizer is a good fertilization practice for modifying soil quality and attaining optimum yield. The obtained findings were in agreement with the study of [29, 32, 33, 36] who also registered that the application of silicic acid considerably improved wheat growth and spike characters in various cereal crops.

Table 3. Effect of silicon sulphate and silicic acid levels on plant height, No. of spikes m^{-2} and spike length of wheat in both seasons.

Treatments	Plant height (cm)		No. of spikes m^{-2}		Spike length (cm)	
	1st season	*2nd season*	*1st season*	*2nd season*	*1st season*	*2nd season*
Ck	$96.00^{e}\pm0.58$	$99.66^{e}\pm0.81$	$382.36^{e}\pm2.94$	$385.43^{f}\pm2.47$	$10.53^{e}\pm0.09$	$10.73^{e}\pm0.09$
SS_1	$105.66^{c}\pm0.67$	$108.66^{c}\pm0.98$	$401.70^{cd}\pm6.11$	$405.23^{cd}\pm5.07$	$12.06^{bc}\pm0.07$	$11.93^{d}\pm0.27$
SS_2	$110.33^{b}\pm0.33$	$114.66^{b}\pm0.85$	$411.56^{ab}\pm4.89$	$417.06^{b}\pm3.42$	$12.43^{ab}\pm0.08$	$12.76^{bc}\pm0.03$
SS_3	$115.00^{a}\pm0.58$	$122.66^{a}\pm0.78$	$417.73^{a}\pm4.71$	$422.93^{a}\pm2.67$	$12.80^{a}\pm0.21$	$13.50^{a}\pm0.21$
SA_1	$101.66^{d}\pm0.33$	$105.00^{d}\pm0.58$	$388.40^{e}\pm3.10$	$393.93^{e}\pm1.87$	$11.20^{d}\pm0.10$	$11.63^{d}\pm0.30$
SA_2	$105.66^{c}\pm0.88$	$109.66^{c}\pm0.72$	$395.63^{d}\pm1.58$	$402.83^{d}\pm1.11$	$11.90^{c}\pm0.15$	$12.50^{c}\pm0.06$
SA_3	$109.33^{b}\pm1.67$	$113.66^{b}\pm0.60$	$404.56^{bc}\pm3.19$	$408.86^{c}\pm2.34$	$12.33^{b}\pm0.12$	$12.96^{b}\pm0.07$

Values are means (±SE) of three replicates. For L.S.D.'s results, means with various letters indicate significant differences among means ($p < 0.05$). Ck, control; SS_1, Silicon Sulphate 50 ppm; SS_2, Silicon Sulphate 100 ppm; SS_3, Silicon Sulphate 150 ppm; SA_1, silicic acid 20 ppm; SA_2, silicic acid 40 ppm; SA_3, silicic acid 60 ppm.

Table 4. Effect of silicon sulphate and silicic acid levels on grains weight $spike^{-1}$ and 1000-grain weight of wheat in both seasons.

Treatments	Grains weight $spike^{-1}$ (g)		1000-grain weight (g)	
	1st season	*2nd season*	*1st season*	*2nd season*
Ck	$4.46^{d}\pm0.09$	$5.03^{e}\pm0.18$	$50.60^{d}\pm0.30$	$52.41^{f}\pm0.63$
SS_1	$5.30^{c}\pm0.06$	$5.73^{c}\pm0.37$	$55.23^{c}\pm1.36$	$58.38^{d}\pm0.48$

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SS_2	$5.76^{b}\pm0.09$	$6.30^{b}\pm0.25$	$59.74^{b}\pm0.97$	$62.76^{b}\pm0.80$
SS_3	$6.03^{a}\pm0.07$	$6.73^{a}\pm0.12$	$63.47^{a}\pm1.10$	$67.66^{a}\pm0.17$
SA_1	$5.10^{c}\pm0.12$	$5.40^{d}\pm0.29$	$53.15^{c}\pm0.18$	$55.49^{e}\pm0.51$
SA_2	$5.26^{c}\pm0.12$	$5.66^{cd}\pm0.32$	$55.59^{c}\pm0.30$	$59.38^{d}\pm0.28$
SA_3	$5.60^{b}\pm0.06$	$5.93^{c}\pm0.30$	$59.46^{b}\pm0.19$	$61.00^{c}\pm0.52$

Values are means (±SE) of three replicates. For L.S.D.'s results, means with various letters indicate significant differences among means ($p < 0.05$). Ck, control; SS_1, Silicon Sulphate 50 ppm; SS_2, Silicon Sulphate 100 ppm; SS_3, Silicon Sulphate 150 ppm; SA_1, silicic acid 20 ppm; SA_2, silicic acid 40 ppm; SA_3, silicic acid 60 ppm.

Yield Parameters:

Effect of Silicon Sulphate Levels

Results indicated that biological yield, straw yield, grain yield and harvest index of wheat (cv., Misr-1) were statistically ($p < 0.05$) affected by foliar application of silicon sulphate with various levels as compared to the control treatment in both seasons (Fig. 1). In comparison to the control, treatment of silicon sulphate at 150 ppm concentration dramatically increased biological yield by 27.99 and 26.17 %, straw yield by 33.39 and 32.65%, grain yield by 7.23 and 8.43 %, and harvest index by 43.50 and 43.53% in both seasons, respectively. The findings results are in agreement with those obtained by [15] who remarked that silicon (Si) application considerably increased the yield and yield-related attributes of the maize under limited moisture conditions. These results were similar to the study of [26, 27, 28] who also recorded that the application of Si greatly increased wheat yield parameters.

Effect of Silicic Acid Levels

Foliar application of silicic acid with various levels significantly ($p < 0.05$) impacted the yield parameters of wheat plants in terms of biological yield, straw yield, grain yield, and harvest index in comparison to the control treatment in both seasons (Fig. 1). Results showed that foliar treatment of silicic acid at 60 ppm concentration to wheat plants significantly increased biological yield by 19.08 and 18.02%, straw yield by 24.64 and 23.55%, grain yield by 7.80 and 7.74%, and harvest index by 34.53 and 33.19% in both seasons, respectively, as compared to the control treatment. In general, results pronounced that the highest values of biological yield, straw yield, grain yield, and harvest index were observed from the plants treated with silicon sulphate at 150 ppm followed by silicic acid at 60 ppm treatment, and the lowest values of preceding parameters were remarked from the plants treated with silicic acid at 20 ppm followed by silicon sulphate at 50 ppm treatment in both seasons, respectively, as compared to the values of the control treatment. These results may be due to the high content of silicic acid as foliar application caused an increase in the grain yield of wheat. Such results are in harmony with those obtained by [16, 46] who pointed out that the application of Si improved maize grain yield and dry matter accumulation. The obtained findings were in agreement with the study of [29, 32, 33, 36] who also registered that the application of silicic acid markedly boosted wheat yield-related attributes.

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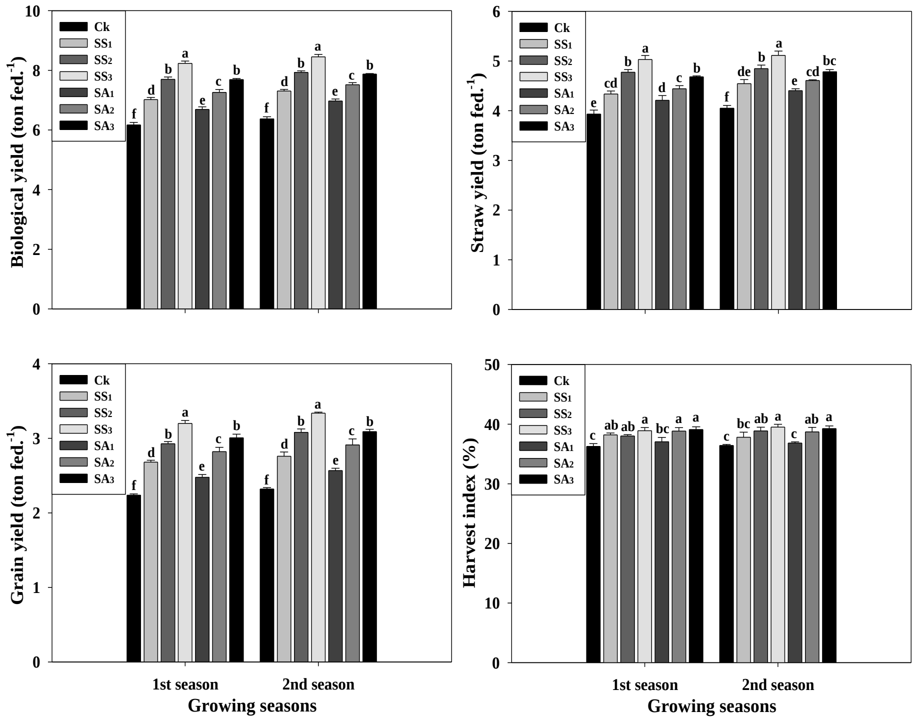

Fig. 1 Effect of silicon sulphate and silicic acid levels on biological yield, straw yield, grain yield and harvest index of wheat in both seasons. Every column in each graph represents the mean (±SE) of three replicates. *Various letters above columns indicate the significant differences among means ($p < 0.05$). Ck, control; SS_1, Silicon Sulphate 50 ppm; SS_2, Silicon Sulphate 100 ppm; SS_3, Silicon Sulphate 150 ppm; SA_1, silicic acid 20 ppm; SA_2, silicic acid 40 ppm; SA_3, silicic acid 60 ppm.*

Grain Mineral Nutrient Concentrations:

Effect of Silicon Sulphate Levels

The presented results revealed that the concentrations of macro/micro-nutrients in wheat grains such as nitrogen (N), phosphorous (P), potassium (K), iron (F), manganese (Mn), and zinc (Zn) were statistically ($p < 0.05$) increased by various levels of silicon sulphate application in comparison to the control treatment in both seasons (Fig. 2). Results revealed that foliar application of silicon sulphate at 150 ppm considerably improved concentrations of N (%) by 136.15 and 78.62%, P (%) by 76.85 and 55.74 %, K (%) by 55.06 and 66.93%, F (ppm) by 29.89 and 21.81 %, Mn (ppm) by 40.60 and 23.01%, and Zn (ppm) by 50.47 and 23.15% in both seasons, respectively, as compared to the values of the control treatment. These results are in agreement with those obtained by [19] found that the 180 kg ha^{-1} of silicon increased nitrogen and phosphate concentrations in the grain and straw of rice. This suggests that silicon in lesser amounts can be beneficial in increasing grain yield and growth of cereal crops. [14] documented that Si application significantly increased Si concentration and uptake in wheat plants grown in sand soil. Also, these results are in agreement with those obtained by [30] carried out the impact of various concentrations of Nano Silica (0, 25, 50, and 100 ppm) on barley varieties under various water conditions, and they suggested that the contents of macro/micronutrient (P, K, Ca, Fe, Zn, and Mn) were increased with increasing levels of Nano Silica. [31] confirmed that the contents of potassium and magnesium in wheat plants were highly increased with the spraying of Si treatment under soil water conditions.

Effect of Silicic Acid Levels

The assessed concentrations of macro/micro-nutrients in wheat grains were significantly ($p < 0.05$) affected by the foliar application of silicic acid with different levels as compared to the control treatment in both seasons (Fig. 2). Foliar treatment of silicic acid at 60 ppm concentration to wheat plants remarkably elevated concentrations of N (%) by 77.82 and 54.41%, P (%) by 43.15 and 35.37%, K (%) by 42.28 and 48.52%, F (ppm) by 25.06 and 17.30%, Mn

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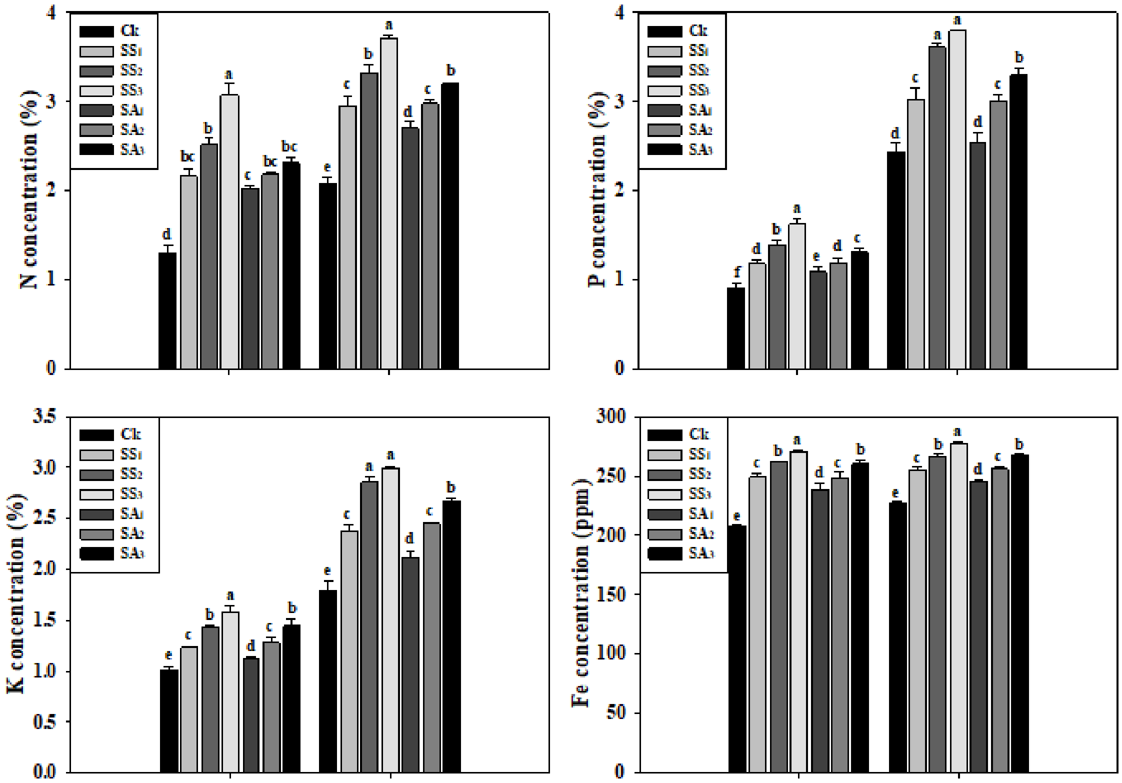
(ppm) by 30.76 and 17.48%, and Zn (ppm) by 43.12 and 15.36% in both seasons, respectively, as compared to the values of the control treatment. Overall, results illustrated that the highest values of macro/micro-nutrient concentrations in wheat grains were found from the plants treated with silicon sulphate at 150 ppm followed by silicic acid at 60 ppm treatment, and the lowest values of the precedent parameters were noticed from the plants treated with silicic acid at 20 ppm followed by silicon sulphate at 50 ppm treatment in both seasons, respectively, as compared to the values of the control treatment. Further, [8] suggested that Si gave the highest values of N, P, and K content in grain under drought conditions in sorghum. Foliar application of silicon substantially elevated the concentration of potassium in oat plants, and this is consistent with [28, 47]. [34] studied the impact of 4 concentrations of soluble Si doses, as mono-silicic acid form (0, 15, 30, and 60 kg ha^{-1}) on corn, and they noticed that concentrations of Si, K, Ca, and P were statistically enhanced with increasing Si dose as compared to the control. [36] revealed that the priming treatment of wheat grain by 300, 600, and 900 mg l^{-1} of Si-NPs considerably boosted the grain concentrations of N, P, and K, as compared to the control treatment.

As mentioned in this study, all previous results suggested that the relative efficacy of Si sources and levels could be considered a promising approach, which could improve plant growth and spike characters (Tables 3 and 4), enhance yield parameters (Fig. 1), and elevate grain nutrient concentrations (Fig. 2), thus they might be regarded as a significant strategy to enhance plant growth, yield-related traits, and grain nutrient in wheat and attain agricultural sustainability under the local study area.



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Research Article

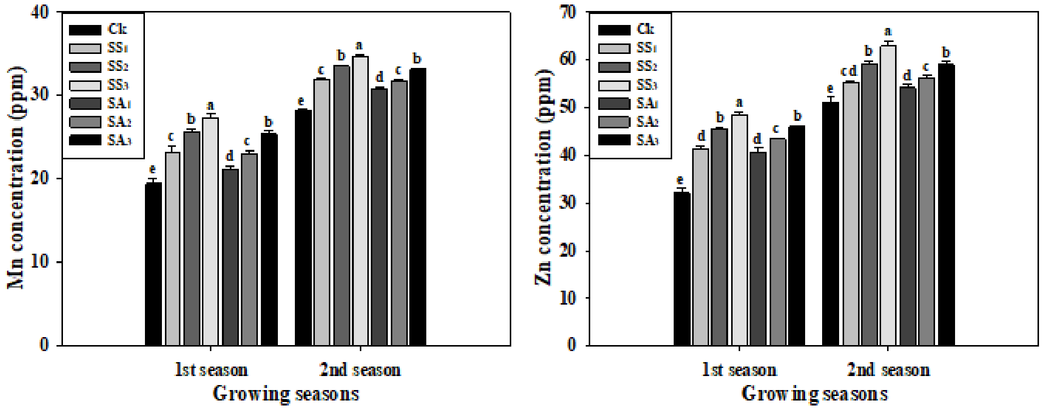

Fig. 2 Effect of silicon sulphate and silicic acid levels on grain nutrients concentrations of nitrogen (N), phosphorous (P), potassium (K), iron (F), manganese (Mn) and zinc (Zn) of wheat in both seasons. *Every column in each graph represents the mean (±SE) of three replicates. Various letters above columns indicate the significant differences among means ($p < 0.05$). Ck, control; SS_1, Silicon Sulphate 50 ppm; SS_2, Silicon Sulphate 100 ppm; SS_3, Silicon Sulphate 150 ppm; SA_1, silicic acid 20 ppm; SA_2, silicic acid 40 ppm; SA_3, silicic acid 60 ppm.*

CONCLUSION

The study found that spraying 150 ppm and 60 ppm concentrations of silicon sulphate and silicic acid to wheat plants effectively increased growth, yield, and grain nutrient levels. In brief, silicon sulphate 150 ppm treatment was most effective in completely appraised characters of wheat followed by silicic acid 60 ppm treatment to enhance wheat yield. It could be concluded that the foliar applications of silicon sulphate and silicic acid at various levels could maximize the wheat yield and attain agricultural sustainability under experimental conditions.

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