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Effect Of Nano- And Conventional Silicon and Potassium on The Availability and Uptake of Silicon, Potassium and Potato Yield Under Water Stress Conditions

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Abstract

This field experiment was conducted in the spring of 2023 at Agricultural Research Station 1 of the College of Agriculture at the University of Anbar in Ramadi, Iraq. It investigated the effect of different levels of nano and conventional potassium (0, 300, 15, 30 kg K_2O ha^{-1} designated K0, Kt, Kn1, and Kn2, respectively), spraying nano silicon (0, and 4 ml L^{-1} or Si0 and Si1, respectively), and different irrigation levels (35, 45, 55% or I1, I2, and I3, respectively) of plant-available water on the available and absorbed concentrations of potassium and silicon, potato yield, some production indicators, element utilization efficiency, and water use efficiency. The results show that water stress level I1 had the highest value for water use efficiency at 5.967 kg m^{-3}. Treatment I1Kt recorded the highest value for available potassium concentration in the soil after harvest, at 181.57 mg kg^{-1}, the highest dry matter yield of aerial parts (4693 kg ha^{-1}), and the highest percentage of dry matter in tubers (22.29%). The I3Kn2 treatment achieved the highest values in potassium concentration in potato tubers (2.335%), total potassium uptake (143.04 kg ha^{-1}), and total silicon uptake (15.54 kg ha^{-1}). The I3Si1 treatment gave the highest value of 0.420% in silicon concentration in the vegetative part, and I1KtSi1 recorded the highest marketable yield with a value of 52.418 Mg ha^{-1}. Treatment I3Kn2Si1 registered the highest potassium concentration in the vegetative part (3.855%) and the highest silicon concentration in tubers (0.338%).

Keywords: Water stress, Silicon, Potassium, Water use efficiency, Fertilizer use efficiency.

تأثير السليكون والبوتاسيوم النانوي والتقليدي في الجاهز والممتص من السليكون والبوتاسيوم وحاصل البطاطا تحت ظروف الإجهاد المائي

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الخلاصة

نفذت خلال الموسم الربيعي لعام 2023 تجربة حقلية في محطة الأبحاث الزراعية 1 التابعة لكلية الزراعة جامعة الأنبار في مدينة الرمادي لمعرفة تأثير مستويات مختلفة من البوتاسيوم النانوي والتقليدي (0 و300 و15 و30 كغم K_2O هـ$^{-1}$) ورموزها K_0 و K_t و Kn_1 و Kn_2 بالتتابع، مع رش السليكون النانوي بتركيزين (0 و4 مل لتر$^{-1}$) ورموزها Si_0 و Si_1 بالتتابع، مع مستويات ري (35 و45 و55%) من الماء الجاهز للنبات ورموزها I_1 وI_2 و I_3 بالتتابع، في تركيز الجاهز والممتص من البوتاسيوم والسليكون وحاصل البطاطا وبعض مدلولات الإنتاج وكفاءة أستعال العنصر وكفاءة استعمال المياه. بينت نتائج التحليل الإحصائي أن مستوى الإجهاد المائي I_1 سجل اعلى قيمة في صفة كفاءة استعمال المياه 5.967 كغم م$^{-3}$. وان المعاملة I_1K_t سجلت اعلى قيمة لتركيز البوتاسيوم الجاهز في التربة بعد الحصاد بقيمة بلغت 181.57 ملغم كغم$^{-1}$ واعلى حاصل للمادة الجافة للأجزاء الهوائية بقيمة بلغت 4693 كغم هـ$^{-1}$ واعلى نسبة مئوية للمادة الجافة في الدرنات بقيمة بلغت 22.29%. وكذلك حققت المعاملة I_3Kn_2 اعلى قيمة في تركيز البوتاسيوم في درنات البطاطا 2.335% وحاصل امتصاص البوتاسيوم الكلي 143.04 كغم هـ$^{-1}$ وحاصل امتصاص السليكون 15.54 كغم هـ$^{-1}$. بينما كانت المعاملة I_3Si_1 الأعلى قيمة 0.420% في صفة تركيز السليكون في الجزء الخضري. وسجلت المعاملة $I_1K_tSi_1$ اعلى قيمة في صفة الحاصل القابل للتسويق بقيمة بلغت 52.418 ميكا غرام هـ$^{-1}$. سجلت المعاملة $I_3Kn_2Si_1$ اعلى قيمة لتركيز البوتاسيوم في الجزء الخضري 3.855% واعلى قيمة لتركيز السليكون في درنات البطاطا 0.338%.

كلمات مفتاحية: الإجهاد المائي، السليكون، البوتاسيوم، كفاءة استعمال المياه، كفاءة استعمال السماد.

Introduction

Water stress is an abiotic environmental stress characterized by a change in the water content in the plant's surrounding environment. Based on this, drought stress is used to describe a deficiency in water, not an excess. Water stress causes a deficit in available water for the plant, initially leading to inhibition of growth in its upper parts, followed by a decrease in cell division and expansion, as well as a reduction in enzyme formation and activity. Increased stress results in the closure of stomata, leading to reduced gas exchange, particularly $CO2$, and increased water evaporation through transpiration, which in turn raises the plant's body temperature. Furthermore, an increased respiration rate is accompanied by a decrease in the transfer of photosynthetic products, lower sugar formation, increased synthesis of amino acids such as proline, and a decline in nutrient uptake and transport (8).

The negative effects of drought stress are evident in most plants, particularly vegetable crops, which are among the most water-intensive crops. This requires the application of various management mechanisms to increase water use efficiency, such as modern, highly efficient irrigation systems or the addition of certain compounds to the soil. Also, beneficial is having plants that have the potential to reduce the amount of water they require, with a focus on ensuring that these strategies do not affect the quantity and characteristics of the crop. The addition of potassium fertilizers is one such method, as potassium plays a crucial role in osmotic regulation, stomatal opening and closing, photosynthesis, enzyme activity, protein synthesis, energy transfer, phloem sap transport, and ketone-anion balance (4). Although silicon is classified as a beneficial nutrient, various researches have demonstrated its clear role in mitigating the effects of various environmental stresses, including water stress (20). Mineral fertilizers are crucial to food production despite their low nutrient uptake efficiency and high nutrient loss. Nanotechnology can enhance crop productivity and reduce nutrient loss, thereby increasing interest in nano-fertilizers (10).

Potatoes, of the Solanaceae family, are the world's fourth most important food crop, after wheat, corn, and rice. They are a major source of energy due to their high carbohydrate and protein content and are also a source of vitamins B and C, as well as many fat-soluble vitamins and minerals, including potassium, phosphorus, iron, copper, zinc, magnesium, and manganese (7). They are grown throughout Iraq, covering an area of approximately 39,000 hectares. However, the decrease in irrigation water volumes has resulted in its relatively low yield of 16.036 Mg/ha (Statistics Bureau, 2024), compared to global production. This low yield is among the most important challenges facing farmers. Based on the above, this research investigated the role of potassium fertilizers (conventional and nano) and nano-silicon on water use efficiency, available and absorbed concentrations of specific nutrients, and potato yield under water-stress conditions.

Materials and Methods

Experimental Implementation Site: A field experiment was conducted at the Agricultural Research Station of the College of Agriculture, University of Anbar, in the Al-Buaita area of Ramadi located on the banks of the Euphrates River. Composite soil samples were taken from a depth of 0-30 cm and passed through a sieve with 2 mm diameter holes to estimate some chemical and physical properties of the study soil (Table 1).

Table 1: Some chemical and physical soil properties.

Characteristics	Value	Unit	Characteristics	Value	Unit
Electrical conductivity	1.68	$ds.m^{-1}$	Bulk Density	1.31	$Mg\ m^{-3}$
pH	7.48	-----	True Density	2.54	
Organic matter	5.80	gkg^{-1}	Sand	684	gk/g^{-1}
Lime	250.37		Silt	204	
Gypsum	1.56		Clay	112	
Available nitrogen	12.31	$mg\ kg^{-1}$	Soil texture	Sandy loam	
Available phosphorus	10.60		Available Water	15.10	%
Available potassium	128.50				

Preparing the Experimental Land: The experimental land was plowed using a rotary-blade plow and a perpendicular tillage. Then, the soil was smoothed, leveled, and divided into 5-m-long and 0.75-m-wide terraces, creating a total area of 3.75 m^2. A distance of 0.75 m was left between terraces, with each terrace representing a single experimental unit.

Agriculture: Borin seeds were planted on 5m x 0.75m beds, 25 cm apart, during spring on January 25, 2023, with a spacing of 35-55 mm in the center of the bed. A 15-cm-deep slit was made in the bed. Twenty tubers were planted in each experimental unit, with each unit containing 20 plants.

Irrigation: T-tape drip irrigation was used, featuring drippers with a discharge rate of 4 liters per hour and a spacing of 0.15 m between drippers. Irrigation was carried out according to the plant's growth stages. Water depths were calculated using the evaporation basin (Epan) and the following equation:

$$ET_O = k_p * E_{Pan}$$

Where:

ET_O: Reference evapotranspiration (Mm Day^{-1}).

k_p: Evaporation basin coefficient (Without units).

E_{Pan}: Evaporation from the basin (Mm Day^{-1}).

Study Factors:

Water Stress:

1. Irrigating when 35% of the plant's available water was depleted, symbolized as (I1).
2. Irrigating when 45% of the plant's available water was depleted (I2).
3. Irrigating when 55% of the plant's available water was depleted (I3).

Factor 2: Potassium

1. Comparison, symbolized as K0.
2. Adding conventional potassium fertilizer at 300 kg K2O ha^{-1} (Kt).
3. Adding nano-potassium fertilizer at 15 kg K2O ha^{-1} (Kn1).
4. Adding nano-potassium fertilizer at 30 kg K2O ha^{-1} (Kn2).

Factor 3: Nano-silicon Fertilization

1. Without spraying, symbolized by (Si0).

2. Spraying nano-silicon fertilizer at 4 ml L^{-1} concentration, symbolized by (Si1).

The plants were foliar fed nano-silicon until thoroughly wet. A spreading agent was sprayed 3 times, 21 days apart between each spray.

Experimental Design: The experiment was implemented as a nested design, with water stress levels as the main plot and potassium and silicon levels as the subplots. It employed a randomized complete block design (RCBD) with three replicates, resulting in 24×3 = 72 experimental units.

Fertilization and Crop Maintenance: Chemical fertilizer was added according to the recommended levels (300 and 300 kg ha^{-1}) (N and P_2O_5) according to (1). All crop maintenance operations were performed.

Statistical Analysis: Results were analyzed using the Genstat program, and averages were compared using the least significant difference (LSD) at a 5% probability level.

Traits Studied:

Soil content of available potassium after harvest (mg kg^{-1} of soil): Available potassium was estimated using a flame photometer after extraction with 0.5 M calcium chloride, as described in the method (12).

Estimating potassium and silicon content in the vegetative part and tubers: Potassium was determined after the plant extract was digested using a flame photometer according to Richards' method (13) while silicon was determined in the leaves and tubers, as described in (17).

Dry matter yield of aerial parts (kg ha^{-1}): Ten plants were randomly harvested from each experimental unit in the area in contact with the soil two weeks prior to uprooting. They were washed with water and air-dried, then dried in an electric oven at 65 °C until the weight stabilized (2). The dry matter was calculated using the formula:

Dry matter yield of aerial parts (kg ha^{-1}) = dry weight of plant × number of plants per hectare.

Dry matter in tubers (%): Five tubers were randomly selected from each experimental unit, sliced into small pieces, and weighed to obtain a wet weight of 100 g. They were then placed in an electric oven at 70 °C until the weight stabilized, as stated by (2). The percentage of dry matter was then calculated according to the following equation:

Dry matter % = (Dry weight of sample - Wet weight of sample) x 100

Potassium and silicon absorption yield in the vegetative part and tubers (kg h^{-1}): The potassium and silicon absorption yield in the aerial parts and tubers was calculated according to the following equation:

Absorption yield (kg h^{-1}) = Element concentration in the dry vegetative part (%) x Dry matter yield of the vegetative part (kg h^{-1}).

Marketable yield (tons ha^{-1}): Calculated based on the yield of the experimental unit's plants after excluding deformed and infected tubers and small tubers (less than 2.5 cm in diameter). Production per hectare was then calculated according to the following equation:

Marketable yield = Marketable yield per plant × Number of plants per hectare

Fertilizer use efficiency (%): Calculated according to the equation mentioned in (1) as follows:

Fertilizer use efficiency % = (Absorption of fertilizer treatment – Absorption of control treatment/Level of added element) × 100

Water Use Efficiency (WUE): WUE was estimated by dividing the total yield (kg ha^{-1}) by the volume of water applied (m3 ha^{-1}) using the formula provided by (9), as follows:

Water use efficiency (kg m^{-3}) = Total yield (kg ha^{-1})/Quantity of added water (m^3 h^{-1}).

Results and Discussion

Potassium concentrationc in the soil (mg kg^{-1} of soil): Table 2 on the effect of adding silicon and nano-potassium on the concentration of available potassium in the soil under water stress conditions shows that adding potassium, whether in the conventional or nano-formulation, achieved significant differences in its concentration in the soil. The Kt treatment recorded the highest value, reaching 161.04 mg kg^{-1}, a 47.6% increase over the K0 treatment, which recorded the lowest value of 109.12 mg kg^{-1}. This increase in potassium concentration in the soil may be due to increased levels of addition, which effectively meet the plant's potassium requirements (14).

The effect of water stress was significant, with level I1 achieving the highest value for the studied trait, recording 159.90 mg kg^{-1}, a 25.7% increase over level I3, which recorded the lowest value of 127.32 mg kg^{-1}. This may be because the process of potassium release in the soil requires hydrolysis and the effectiveness of hydrogen ions, meaning that the soil solution plays a significant role in the movement of potassium in the root zone. Nano-silicon spraying reached a significant level, with Si1 outperforming Si0 by 0.6%, recording 143.03 and 142.14 mg kg^{-1}, respectively. This may be due to the spraying reducing plant potassium uptake by enhancing passive immunity, as it forms a physical barrier on the leaf surface and the osmotic effects associated with silicon (19). The binary and triple interaction between the study factors did not have significant effects, except in the case of the binary interaction of water stress with potassium. This achieved the highest value of 181.57 mg kg^{-1} for the I1Kt treatment, 85.2% over the I3K0 treatment which had the lowest value 98.03 mg kg^{-1}.

Table 2: Effect of nano-silicon and potassium on the soil content's available potassium post-harvest (mg kg^{-1} soil) under water stress conditions.

Water stress	Silicon	Potassium				Water stress and silicon interaction
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	
I1 (35% exhaustion)	Si_0 (0 ml l^{-1})	120.07	181.98	164.77	171.84	159.66
	Si_1 (4 ml l^{-1})	121.09	181.15	166.13	172.18	160.14
I2 (45% exhaustion)	Si_0 (0 ml l^{-1})	107.72	157.18	140.28	155.80	140.25
	Si_1 (4 ml l^{-1})	109.78	157.75	140.76	155.69	140.99
I3 (55% exhaustion)	Si_0 (0 ml l^{-1})	97.73	143.51	126.69	138.10	126.51
	Si_1 (4 ml l^{-1})	98.33	144.67	128.51	140.28	127.95
LSD at 0.05 for triple interference		NS				NS
Mean of Potassium		109.12	161.04	144.52	155.65	
LSD 0.05		1.086				
Water stress X potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Water Stress
I1 (35% exhaustion)		120.58	181.57	165.45	172.01	159.90
I2 (45% exhaustion)		108.75	157.47	140.52	155.75	140.62
I3 (55% exhaustion)		98.03	144.09	127.60	139.19	127.23
LSD 0.05		2.277				1.859
Silicon X Potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Silicon
Si_0 (0 ml l^{-1})		108.51	160.89	143.91	155.25	142.14
Si_1 (4 ml l^{-1})		109.73	161.19	145.13	156.05	143.03
LSD 0.05		NS				0.839

Potassium concentrations in the vegetative part of the plant (%): The analysis results in Table 3, on the effect of adding silicon and potassium nanoparticles on potassium concentration in the vegetative part of the plant under water stress conditions, indicated that the differences were significant for all averages and binary and triple interactions. The Kt level was significantly higher in potassium averages, with a value of 3.248%, representing a 23.3% increase compared to K0, which had a lower value of 2.634%. This increase in potassium concentration when adding potassium fertilizer may be due to the higher addition effectively supplying the plant with its potassium requirements, thereby increasing its absorption and concentration in the tissues. For water stress, the third level (I3) had the highest value for the trait under study, at 3.581%, representing a 33.7% increase over the lowest value of 2.678% for the first water stress level (I1). The decrease in potassium concentrations in the vegetative part of the first water stress level (I1) may be attributed to the possibility potassium concentrations being diluted in the plant due to dense plant growth.

Regarding silicon application, the Si1 level increased by 0.93% over Si0, with the two levels recording averages of 3.011% and 2.983%, respectively. The KtSi1 treatment achieved the highest value in the binary interaction between potassium and silicon, at 3.260%, representing a 24.4% increase, compared to the K0Si0 treatment, which recorded the lowest value of 2.620%. For the water stress and silicon interactions, the highest value was observed for I3Si1, which recorded 3.613%, representing a 35.1% increase over the lowest treatment value, I1Si0, of 2.674%. The interaction of water stress with potassium had a significant effect, with the highest increase of 66.6% for the I3Kn2 treatment, with a value of 3.831%, compared to the I1K0 treatment, which had a lower value of 2.300%. The highest percentage increase, at 67.8%, occurred in the triple interaction of the study factors for I3Kn2Si1, compared to the I1K0Si0 treatment, which had the lowest value. The treatments recorded values of 3.855% and 2.297%, respectively.

Table 3: The effect of nano-silicon and potassium on potassium concentrations in the vegetative part of the plant (%) under water stress conditions.

Water stress	Silicon	Potassium				Water stress and silicon interaction
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	
I1 (35% exhaustion)	Si_0 (0 ml l^{-1})	2.297	2.977	2.610	2.810	2.674
	Si_1 (4 ml l^{-1})	2.302	2.984	2.625	2.818	2.682
I2 (45% exhaustion)	Si_0 (0 ml l^{-1})	2.426	2.993	2.654	2.833	2.726
	Si_1 (4 ml l^{-1})	2.437	3.002	2.665	2.844	2.737
I3 (55% exhaustion)	Si_0 (0 ml l^{-1})	3.136	3.738	3.515	3.807	3.549
	Si_1 (4 ml l^{-1})	3.206	3.793	3.600	3.855	3.613
LSD at 0.05 for triple interference		0.0074				0.0055
Mean of Potassium		2.634	3.248	2.945	3.161	
LSD 0.05		0.0030				
Water stress X potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Water Stress
I1 (35% exhaustion)		2.300	2.981	2.617	2.814	2.678
I2 (45% exhaustion)		2.431	2.997	2.659	2.838	2.731
I3 (55% exhaustion)		3.171	3.766	3.557	3.831	3.581
LSD 0.05		0.0065				0.0054
Silicon X Potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Silicon
Si_0 (0 ml l^{-1})		2.620	3.236	2.926	3.150	2.983
Si_1 (4 ml l^{-1})		2.648	3.260	2.963	3.172	3.011
LSD 0.05		0.0037				0.0016

Potassium concentrations in the potato tubers (%): Table 4 presents the effect of adding silicon and nano potassium on potassium concentration in potato tubers under water-stress conditions. The potassium averages show that the Kt treatment achieved the highest value of 1.847%, a significant 29% increase compared to the K0 treatment's lowest value of 1.431%. There were significant differences between potassium averages according to the LSD value. Silicon increases osmotic forces or stimulates the transfer of potassium into the xylem sap. Adding silicon can improve root growth, which increases water absorption, nutrient uptake, and their transport within the plant, thereby increasing their concentration, including potassium.

Regarding water stress averages, the differences were statistically significant, with I3 recording the highest value of 2.035%, a 51.6% increase over level I1, which recorded the lowest value of 1.342%. As for silicon spraying, level Si1 recorded a significant increase of 3.5%, at 1.706%, compared to level Si0, which recorded 1.649%. The binary interaction of the potassium and water stress also had significant differences. Treatment I3Kn2 achieved the highest value, with a percentage increase of 114.6% compared to treatment I1K0, which had the lowest value for this level. The two treatments yielded rates of 2.335% and 1.088%, respectively. The effects of the remaining binary and triple interactions were insignificant.

Table 4: Effect of nano-silicon and potassium on potassium concentrations in the potato tubers (%) under water stress conditions.

Water stress	Silicon	Potassium				Interaction between water stress and silicon
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	
I1 (35% exhaustion)	Si_0 (0 ml l^{-1})	1.063	1.516	1.226	1.460	1.316
	Si_1 (4 ml l^{-1})	1.113	1.590	1.303	1.463	1.367
I2 (45% exhaustion)	Si_0 (0 ml l^{-1})	1.456	1.876	1.543	1.613	1.622
	Si_1 (4 ml l^{-1})	1.483	1.896	1.646	1.743	1.692
I3 (55% exhaustion)	Si_0 (0 ml l^{-1})	1.740	2.050	1.923	2.326	2.010
	Si_1 (4 ml l^{-1})	1.730	2.153	2.013	2.343	2.060
LSD at 0.05 for triple interference		NS				NS
Mean of Potassium		1.431	1.847	1.609	1.825	
LSD 0.05		0.0221				
Water stress X potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Water Stress
I1 (35% exhaustion)		1.088	1.553	1.265	1.461	1.342
I2 (45% exhaustion)		1.470	1.886	1.595	1.678	1.657
I3 (55% exhaustion)		1.735	2.101	1.968	2.335	2.035
LSD 0.05		0.0350				0.0146
Silicon X Potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Silicon
Si_0 (0 ml l^{-1})		1.420	1.814	1.564	1.800	1.649
Si_1 (4 ml l^{-1})		1.442	1.880	1.654	1.850	1.706
LSD 0.05		NS				0.0198

Silicon concentrations in the vegetative part of the plant (%): The addition of nano-silicon and potassium affected silicon concentration in the vegetative part of the plant under water stress conditions (Table 5). The Kn2 treatment had the highest value, 0.323%, a significant increase of 1.6% compared to K0, which recorded the lowest value at 0.318%. This may be attributed to the important role of nano-silicon in regulating the absorption and transport of nutrients across cell membranes and maintaining ionic balance within them (15). Water stress significantly affected this trait, as the third level, I3, outperformed the first, I1, with a significant increase of 81.2%, recording values of 0.415% and 0.229%, respectively. This may be attributed to the increased silicon concentration in the vegetative part, resulting from higher levels of its addition under water stress conditions, which reduces the water stress to which the plant is exposed.

As for silicon spraying, the Si1 level achieved a higher value of 0.333%, a significant increase of 7.8% over the Si0 level, which recorded a lower value of 0.309%. This may be attributed to nano-silicon's extremely high plant absorption capacity, surface area, and controlled release, leading to better nutrient delivery to targeted sites (20). The results in the same table show that the two-way interaction between water stress and silicon was significant in terms of silicon concentration in the plant. The lowest value was for the I1Si0 treatment, which yielded a value of 0.215%, compared to the I3Si1 treatment (0.420%) which registered a significant increase of 95.3%.

For the potassium with water stress interaction, the results were significant, with treatments I3Kn1 and I3Kn2 outperforming I1K0 by 0.416% and 84%, respectively. Treatment I1K0 recorded the lowest value of 0.226%. The Kn2Si1 treatment recorded the highest value of 0.337%, which was 9.8% above the K0Si0 treatment’s lowest value of 0.307% in the binary interaction between potassium and silicon. In contrast, the triple interaction between the study factors did not differ significantly in the studied trait.

Table 5: The effect of nano-silicon and potassium on silicon concentrations in the vegetative part of the plant (%) under water stress conditions.

Water stress	Silicon	Potassium				Interaction between water stress and silicon
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	
I1 (35% exhaustion)	Si_0 (0 ml l^{-1})	0.212	0.217	0.216	0.216	0.215
	Si_1 (4 ml l^{-1})	0.239	0.249	0.241	0.245	0.243
I2 (45% exhaustion)	Si_0 (0 ml l^{-1})	0.301	0.301	0.305	0.307	0.303
	Si_1 (4 ml l^{-1})	0.331	0.338	0.333	0.341	0.336
I3 (55% exhaustion)	Si_0 (0 ml l^{-1})	0.408	0.410	0.414	0.408	0.410
	Si_1 (4 ml l^{-1})	0.417	0.421	0.418	0.424	0.420
LSD at 0.05 for triple interference		NS				0.0028
Mean of Potassium		1.431	1.847	1.609	1.825	
LSD 0.05		0.0016				
Water stress X potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Water Stress
I1 (35% exhaustion)		0.226	0.233	0.228	0.231	0.229
I2 (45% exhaustion)		0.316	0.319	0.319	0.324	0.319
I3 (55% exhaustion)		0.412	0.415	0.416	0.416	0.415
LSD 0.05		0.0032				0.0024
Silicon X Potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Silicon
Si_0 (0 ml l^{-1})		0.307	0.309	0.311	0.310	0.309
Si_1 (4 ml l^{-1})		0.329	0.336	0.330	0.337	0.333
LSD 0.05		0.0026				0.0014

Silicon concentrations in potato tubers (%): The results in Table 6 demonstrate the effect of adding nano-silicon and potassium on silicon concentration in potato tubers under water stress conditions. Significant differences were observed for all study factors, whether individually or in combination, whether double or triple. Treatment Kn2 had the highest potassium mean value at 0.223%, representing a 4.2% increase compared to treatment K0, which had the lowest value at 0.214%. The third water stress level (I3) achieved a significant value of 0.317%, the highest, representing a 168.6% increase over the first (I1) which had the lowest value of 0.118%. Level Si1 had a higher value than level Si0, representing a 10% increase, with the two recording values of 0.230% and 0.209%, respectively, in the silicon spray averages.

Treatments I3Kt and I3Kn2 showed a significant increase of 0.321% for both, with a notable increase of 176.7% over the I1K0 treatment, which had a lower value of 0.116% due to the dual interaction between water stress and potassium. The analysis of variance showed that the interaction between potassium and silicon was significant, with Kn2Si1 treatment achieving the highest value of 0.237%, a 15% increase over the K0Si0 treatment, which had the lowest value of 0.206%.

Regarding the dual interaction of water stress and silicon, the I3Si1 treatment outperformed I1Si0, with a significant increase of 188.6%, with both treatments recording 0.329% and 0.114%, respectively. Also, the triple interaction of the study factors was significant in the silicon concentration trait in potato tubers, with the I3Kn2Si1 treatment achieving the highest value of 0.338%, a 204.5% increase over the lowest treatment (I1K0Si0), which recorded a value of 0.111%.

Table 6: Effect of nano-silicon and potassium on silicon concentrations in potato tubers (%) under water stress conditions.

Water stress	**Silicon**	**Potassium**				**Interaction between water stress and silicon**
		K_0 (0 kg K_2O ha^{-1})	**K_t (300 kg K_2O ha^{-1})**	**Kn_1 (15 kg K_2O ha^{-1})**	**Kn_2 (30 kg K_2O ha^{-1})**	
I1 (35% exhaustion)	Si_0 (0 ml l^{-1})	0.111	0.115	0.117	0.113	0.114
	Si_1 (4 ml l^{-1})	0.121	0.126	0.119	0.122	0.122
I2 (45% exhaustion)	Si_0 (0 ml l^{-1})	0.201	0.205	0.209	0.212	0.207
	Si_1 (4 ml l^{-1})	0.228	0.244	0.237	0.251	0.240
I3 (55% exhaustion)	Si_0 (0 ml l^{-1})	0.306	0.308	0.307	0.305	0.306
	Si_1 (4 ml l^{-1})	0.318	0.335	0.325	0.338	0.329
LSD0.05 for triple interference		0.0042				0.0023
Mean of Potassium		0.214	0.222	0.219	0.223	
LSD 0.05		0.0017				
Water stress X potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Water Stress
I1 (35% exhaustion)		0.116	0.121	0.118	0.118	0.118
I2 (45% exhaustion)		0.215	0.224	0.223	0.231	0.223
I3 (55% exhaustion)		0.312	0.321	0.316	0.321	0.317
LSD 0.05		0.0031				0.0020
Silicon X Potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Silicon
Si_0 (0 ml l^{-1})		0.206	0.209	0.211	0.210	0.209
Si_1 (4 ml l^{-1})		0.222	0.235	0.227	0.237	0.230
LSD 0.05		0.0024				0.0012

Dry matter in tubers (%): Table 7 shows the significant positive effect of adding nano-silicon and potassium on the dry matter content in tubers under water stress conditions. The Kt treatment outperformed K0 by 20% at 20.46% compared to 17.04%. This is attributed to potassium's significant role in transporting processed materials to their storage sites in fruit. In the case of water stress, level I1 (20.48%) significantly outperformed level I3 (17.32%) by 18.2%. The reason for I3's lower stress level may be attributed to the fact that water stress reduces the vital activities taking place in the vegetative system which disrupts functional processes such as carbon metabolism, respiration, water absorption, and nutrients. This negatively affects cell division processes, leading to a decrease in the number of dividing cells, which in turn reduces the accumulated dry matter in the fruits (6).

The results indicated a significant difference in dry matter content in the tubers when spraying nano-silicon, with Si1 achieving the highest value at 19.21%, a 1.4% increase compared to Si0 which registered 18.95%. The results showed the significance of the interaction between water stress and potassium, with the I1Kt treatment recording the highest value of 22.29%, representing a 43.3% increase compared to the I3K0 treatment, which had the lowest value of 15.56%. In contrast, the remaining binary and triple interactions had no significant effects.

Table 7: Effect of nano-silicon and potassium on dry matter content (%) in the tubers under water stress conditions.

Water stress	**Silicon**	**Potassium**				**Interaction between water stress and silicon**
		K_0 (0 kg K_2O ha^{-1})	**K_t (300 kg K_2O ha^{-1})**	**Kn_1 (15 kg K_2O ha^{-1})**	**Kn_2 (30 kg K_2O ha^{-1})**	
I1 (35% exhaustion)	Si_0 (0 ml l^{-1})	18.03	22.22	19.38	21.72	20.34
	Si_1 (4 ml l^{-1})	18.30	22.36	19.83	22.01	20.63
I2 (45% exhaustion)	Si_0 (0 ml l^{-1})	17.23	20.77	18.93	20.22	19.28
	Si_1 (4 ml l^{-1})	17.59	21.06	19.42	20.36	19.61
I3 (55% exhaustion)	Si_0 (0 ml l^{-1})	15.41	18.15	17.48	17.94	17.24
	Si_1 (4 ml l^{-1})	15.71	18.22	17.71	17.94	17.39
LSD at 0.05 for triple interference		NS				NS
Mean of Potassium		17.04	20.46	18.79	20.03	
LSD 0.05		0.3498				
Water stress X potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Water Stress
I1 (35% exhaustion)		18.16	22.29	19.61	21.86	20.48
I2 (45% exhaustion)		17.41	20.91	19.17	20.29	19.45
I3 (55% exhaustion)		15.56	18.19	17.59	17.94	17.32
LSD 0.05		0.9306				0.8546
Silicon X Potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Silicon
Si_0 (0 ml l^{-1})		16.89	20.38	18.60	19.96	18.95
Si_1 (4 ml l^{-1})		17.20	20.55	18.98	20.10	19.21
LSD 0.05		NS				0.1926

Dry matter yield of aerial parts (kg ha^{-1}): Table 8 presents the effect of adding nano-silicon and potassium on the dry matter yield of aerial parts under water-stress conditions with the highest yield recorded for the potassium medium in the Kt treatment at 4017 kg ha^{-1}. This treatment significantly outperformed the other, with a 32% increase over K0 which had the lowest value of 3043 kg ha^{-1}. Potassium helps stimulate the formation of ATP, which is necessary to transport materials produced by photosynthesis through the sieve tubes and to form compounds with large molecular weights, such as carbohydrates and proteins, thereby increasing the plant's dry weight. These results are consistent with those reported in (3).

The results also show the significance of water stress levels. The first level, I1, was the highest, recording 4124 kg ha^{-1}, an increase of 32.2% over I3, which had the lowest value of 3119 kg ha^{-1}. The direct effect of drought on plant cell wall expansion, which includes plant cell elongation and the ability of cell walls to expand, reduces turgor potential due to the imbalance in plant water content. This leads to a decline or even complete cessation of growth in water-stressed environments, which affects the dry weight of the plant (6). As for silicon levels, Si1 was the highest, recording 3634 kg ha^{-1}, an increase of 2% over the Si0 level, which was 3565 kg ha^{-1}. This increase is attributed to the role of silicon in enhancing the vegetative characteristics and, ultimately, the dry weight of the potato vegetative system.

For the two-way interaction of water stress and potassium, the I1Kt treatment had the highest value of 4693 kg ha^{-1}, a 90.6% increase over I3K0 which recorded the lowest value of 2462 kg ha^{-1}. There were no significant effects of the three-way interaction between the study factors and the two-way interaction between silicon and potassium.

Table 8: Effect of nano-silicon and potassium on the dry matter yield of aerial parts (kg h^{-1}) under water stress conditions.

Water stress	**Silicon**	**Potassium**				**Interaction between water stress and silicon**
		K_0 (0 kg K_2O ha^{-1})	**K_t (300 kg K_2O ha^{-1})**	**Kn_1 (15 kg K_2O ha^{-1})**	**Kn_2 (30 kg K_2O ha^{-1})**	
I1 (35% exhaustion)	Si_0 (0 ml l^{-1})	3519	4639	3893	4319	4093
	Si_1 (4 ml l^{-1})	3573	4746	3946	4355	4155
I2 (45% exhaustion)	Si_0 (0 ml l^{-1})	3093	3910	3413	3679	3524
	Si_1 (4 ml l^{-1})	3146	3946	3519	3733	3586
I3 (55% exhaustion)	Si_0 (0 ml l^{-1})	2417	3395	2826	3679	3079
	Si_1 (4 ml l^{-1})	2506	3466	2879	3786	3159
LSD at 0.05 for triple interference		NS				NS
Mean of Potassium		3043	4017	3413	3925	
LSD 0.05		41.22				
Water stress X potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Water Stress
I1 (35% exhaustion)		3546	4693	3919	4337	4124
I2 (45% exhaustion)		3119	3929	3466	3706	3555
I3 (55% exhaustion)		2462	3430	2853	3733	3119
LSD 0.05		67.89				35.78
Silicon X Potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Silicon
Si_0 (0 ml l^{-1})		3010	3982	3377	3893	3565
Si_1 (4 ml l^{-1})		3075	4053	3449	3958	3634
LSD 0.05		NS				33.22

Potassium uptake in the vegetative parts and tubers (kg ha^{-1}): Table 9 shows the effect of silicon and nano-potassium on the potassium absorption yield in the vegetative part and tubers under water stress conditions. It is evident that adding potassium, whether in conventional or nano-formulation, yielded significant differences in total potassium absorption. The Kt treatment achieved a value of 128.9 kg ha^{-1}, a 64.3% increase over K0 which recorded the lowest value of 78.51 kg ha^{-1}. This may be because adding large quantities of potassium to the peri-root zone increased potassium availability, helping to form an efficient root system capable of absorbing potassium. This, in turn, increased production and facilitated the movement of processed materials and potassium from the vegetative parts to the tubers.

Regarding the average water stress levels, the highest value was 112.9 kg ha^{-1} for level I3, representing a 15.6% increase over level I2, which had the lowest value of 97.76 kg ha^{-1}. This increased potassium uptake may be due to the fact that all growth indicators, such as plant height, leaf area, number of primary aerial stems, dry weight of the vegetative system, and marketable plant yield, were relatively lower. This means that the increase in the absorbed amount was at the expense of the added amount of potassium, whereby the absorbed potassium was accumulated and ineffective in improving some other traits due to the high water stress conditions at this level.

The Si1 level achieved a significant increase of 2.8%, recording 108.9 kg ha^{-1} compared to the Si0 level, which recorded the lowest value of 105.9 kg ha^{-1}. This may be attributed to silicon's role in increasing plant tolerance to water stress, improving cell wall properties, and impacting root growth and nutrient uptake, particularly potassium and water absorption (11).

In the case of a dual interaction between water stress and potassium, the I3Kn2 treatment achieved the highest value of 143.04 kg ha^{-1}, representing an 88.5% increase compared to the I2K0 treatment, which recorded the lowest value of 75.87 kg ha^{-1}. Meanwhile, for the water stress and silicon interaction, the highest value was 115.3 kg h^{-1} for I3Si1, representing a 19.3% increase compared to I2Si0, which recorded the lowest value of 96.74 kg h^{-1}. The binary interaction between potassium and silicon, as well as the triple interaction between the study factors, had no significant effects.

Table 9: Effect of nano-silicon and potassium on total potassium uptake ($kg\ h^{-1}$) under water stress conditions.

Water stress	Silicon	Potassium				Interaction between water stress and silicon
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	
I1 (35% exhaustion)	Si_0 (0 ml l^{-1})	80.88	138.1	101.6	121.4	110.5
	Si_1 (4 ml l^{-1})	82.28	141.6	103.6	122.7	112.5
I2 (45% exhaustion)	Si_0 (0 ml l^{-1})	75.05	117.06	90.60	104.2	96.74
	Si_1 (4 ml l^{-1})	76.68	118.4	93.81	106.1	98.79
I3 (55% exhaustion)	Si_0 (0 ml l^{-1})	75.82	126.9	99.37	140.1	110.5
	Si_1 (4 ml l^{-1})	80.36	131.5	103.6	145.9	115.3
LSD at 0.05 for triple interference		NS				1.348
Mean of Potassium		78.51	128.9	98.78	123.4	
LSD 0.05		1.340				
Water stress X potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Water Stress
I1 (35% exhaustion)		81.58	139.9	102.6	122.09	111.5
I2 (45% exhaustion)		75.87	117.7	92.20	105.2	97.76
I3 (55% exhaustion)		78.09	129.2	101.5	143.04	112.9
LSD 0.05		2.125				0.902
Silicon X Potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Silicon
Si_0 (0 ml l^{-1})		77.25	127.3	97.19	121.9	105..9
Si_1 (4 ml l^{-1})		79.78	130.5	100.3	124.9	108.9
LSD 0.05		NS				0.918

Silicon uptake in the vegetative part and tubers ($kg\ ha^{-1}$): Table 10 shows the effect of nano-silicon and potassium on silicon uptake in the vegetative part and tubers under water stress conditions. There were significant differences in the averages of the study factors and the two-way interactions between them. The Kt treatment achieved the highest value of 12.60 $kg\ ha^{-1}$, a 34.7% increase over the K0 treatment, which recorded the lowest value of 9.36 $kg\ ha^{-1}$. This may be attributed to the increased vegetative and root growth resulting from the addition of potassium, which leads to an increase in the nutrients manufactured and accumulated in the plant as a result of photosynthesis, such as carbohydrates, whose increase is directly linked to the increase in the silicon content of the grains (21). The differences in water stress levels were significant, as level I3 achieved the highest rate of 12.96 $kg\ ha^{-1}$ or 36.5% over level I1 which recorded the lowest value of 9.50 $kg\ ha^{-1}$. This may be attributed to the increase in silicon concentration in the plant with increasing levels of its addition under water stress (11). Silicon levels Si1 had the highest value of 11.84 $kg\ ha^{-1}$, an increase of 10.3% compared to the Si0 treatment, which recorded the lowest value of 10.73 $kg\ ha^{-1}$. This may be attributed to the foliar application of nano-silicon, which compensates for the soil deficiency resulting from its inability to supply or release elements to the plant, including silicon (5), leading to an increase in silicon absorption.

The results of the statistical analysis showed significant differences in the binary interaction between potassium and water stress and the superiority of the I3Kn2 treatment over the others, recording the highest value of 15.55 kg ha^{-1}, an increase of 93.9% over the lowest treatment I1K0, which had a value of 8.02 kg ha^{-1}. There were significant differences in the binary interaction between water stress and silicon, as the I3Si1 treatment had the highest average of 13.29 kg ha^{-1} across all treatments for this interaction, representing a 50.4% increase compared to the lowest average of the I1Si0 treatment, which was 8.84 kg ha^{-1}. Additionally, the interaction of potassium with silicon resulted in significant differences, with the KtSi1 treatment achieving the highest value of 13.27 kg ha^{-1}, or a 49.1% increase compared to the K0Si0 treatment, which yielded the lowest value of 8.90 kg ha^{-1}. Meanwhile, there were no significant effects of the three-way interaction between the study factors.

Table 10: Effect of nano silicon and potassium on total silicon uptake (kg h^{-1}) under water stress conditions.

Water stress	Silicon	Potassium K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Interaction between water stress and silicon
I1 (35% exhaustion)	Si_0 (0 ml l^{-1})	7.486	10.09	8.436	9.344	8.841
	Si_1 (4 ml l^{-1})	8.552	11.85	9.511	10.69	10.15
I2 (45% exhaustion)	Si_0 (0 ml l^{-1})	9.332	11.77	10.40	11.32	10.70
	Si_1 (4 ml l^{-1})	10.42	13.34	11.73	12.74	12.06
I3 (55% exhaustion)	Si_0 (0 ml l^{-1})	9.874	13.92	11.70	15.02	12.63
	Si_1 (4 ml l^{-1})	10.46	14.60	12.03	16.06	13.29
LSD at 0.05 for triple interference		NS				0.1841
Mean of Potassium		9.355	12.59	10.63	12.53	
LSD 0.05		0.1776				
Water stress X potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Water Stress
I1 (35% exhaustion)		8.019	10.97	8.973	10.02	9.497
I2 (45% exhaustion)		9.879	12.55	11.07	12.03	11.38
I3 (55% exhaustion)		10.16	14.26	11.87	15.54	12.96
LSD 0.05		0.2914				0.1513
Silicon X Potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Silicon
Si_0 (0 ml l^{-1})		8.897	11.93	10.18	11.89	10.72
Si_1 (4 ml l^{-1})		9.813	13.26	11.09	13.16	11.83
LSD 0.05		0.2253				0.1058

Marketable yield (megagrams ha^{-1}): Table 11, on the effect of nano-silicon and potassium on marketable yield under water stress conditions, show significant differences in the means of the study factors and the binary and triple interactions between the factors. For potassium averages, the Kt treatment achieved the highest value of 44.463 Mg ha^{-1}, a 26% increase over the K0 treatment, which had the lowest value of 35.275 Mg ha^{-1}. This is attributed to the positive effect on yield traits due to potassium's significant role in increasing enzyme activity and regulating vital processes within plant tissues, including stimulating flowering and fruit set (4).

The differences between water stress levels were also significant, with level I1 achieving the highest rate of 45.799 Mg ha^{-1}, a 31.8% increase over level I3, which recorded the lowest value of 34.758 Mg ha^{-1}. Exposing plants to water stress upsets water distribution and reduces nutrients, causing flowers to wilt and fall and decreasing their number. This affects the transformation of the vegetative apical meristems into floral ones, thus reducing plant yield. It reduces the vital activities in the vegetative system and disrupts functional processes such as carbon metabolism, respiration, and water and nutrient absorption, negatively affecting yield.

Silicon (Si1) had a higher value of 40.846 Mg h^{-1}, representing a 3.6% increase compared to Si0 (39.431 Mg h^{-1}). This may be attributed to its role in increasing plant tolerance to drought stress through several mechanisms. These include mitigating reactive oxygen species (ROS) and influencing the regulation of osmotic potential by increasing the accumulation of soluble sugars and amino acids in the xylem sap, which increases the osmotic driving force, or by activating the transport of potassium into the xylem sap.

Silicon addition can improve root growth, thereby increasing water uptake and translocation within the plant and enhancing plant resistance to drought. This is due to its role in enhancing vegetative growth traits, including stomatal closure and opening, which delays leaf senescence and maintains the efficiency of carbon metabolism throughout the growing season. Silicon had a positive and significant effect on the number of tubers and yield per plant, thereby positively impacting total marketable yield. The results showed that the interaction of potassium with silicon was significant, with KtSi1 recording the highest value of 45.360 Mg h^{-1}, a 30.9% increase over K0Si0, which recorded the lowest value of 34.649 Mg h^{-1}. The dual interaction of water stress with silicon was significant, and the I1Si1 treatment outperformed, with the highest average of 46.391 Mg h^{-1}, representing a 35.8% increase compared to the lowest average of the I3Si0 treatment, which was 34.153 Mg h^{-1}.

The I1Kt treatment outperformed, with the highest value of 50.871 Mg h^{-1}, representing a 65.4% increase compared to the lowest treatment, I3K0, which recorded a value of 30.764 Mg h^{-1} in the case of dual interaction of potassium with water stress. The results also show the significance of the triple interaction between the study factors, with the highest recorded in the I1KtSi1 treatment, at 52.418 Mg h^{-1}, representing a 75.4% increase compared to the I3K0Si0 treatment, which recorded the lowest value of 29.884 Mg h^{-1}.

Table 11: Effect of nano-silicon and potassium on marketable yield (Mg h^{-1}) under water stress conditions.

Water stress	Silicon	Potassium K$_0$ (0 kg K_2O ha^{-1})	K$_t$ (300 kg K_2O ha^{-1})	Kn$_1$ (15 kg K_2O ha^{-1})	Kn$_2$ (30 kg K_2O ha^{-1})	Interaction between water stress and silicon
I1 (35% exhaustion)	Si$_0$ (0 ml l^{-1})	40.391	49.324	43.920	47.191	45.206
	Si$_1$ (4 ml l^{-1})	40.738	52.418	44.284	48.124	46.391
I2 (45% exhaustion)	Si$_0$ (0 ml l^{-1})	33.671	45.529	37.013	39.520	38.933
	Si$_1$ (4 ml l^{-1})	35.324	46.702	37.413	43.706	40.786
I3 (55% exhaustion)	Si$_0$ (0 ml l^{-1})	29.884	35.849	33.555	37.324	34.153
	Si$_1$ (4 ml l^{-1})	31.644	36.960	34.595	38.249	35.362
LSD at 0.05 for triple interference		0.4376				0.2882
Mean of Potassium		35.275	44.463	38.463	42.352	
LSD 0.05		0.1744				
Water stress X potassium						
		K$_0$ (0 kg K_2O ha^{-1})	K$_t$ (300 kg K_2O ha^{-1})	Kn$_1$ (15 kg K_2O ha^{-1})	Kn$_2$ (30 kg K_2O ha^{-1})	Means for Water Stress
I1 (35% exhaustion)		40.564	50.871	44.102	47.657	45.799
I2 (45% exhaustion)		34.497	46.115	37.213	41.613	39.860
I3 (55% exhaustion)		30.764	36.404	34.075	37.786	34.758
LSD 0.05		0.3487				0.2727
Silicon X Potassium						
		K$_0$ (0 kg K_2O ha^{-1})	K$_t$ (300 kg K_2O ha^{-1})	Kn$_1$ (15 kg K_2O ha^{-1})	Kn$_2$ (30 kg K_2O ha^{-1})	Means for Silicon
Si$_0$ (0 ml l^{-1})		34.649	43.567	38.163	41.345	39.431
Si$_1$ (4 ml l^{-1})		35.902	45.360	38.764	43.360	40.846
LSD 0.05		0.2323				0.1161

Water use efficiency (kg m^{-3}): Table 12 illustrates the impact of adding silicon and nano-potassium on water use efficiency (kg m^{-3}) under water stress conditions. Potassium from both sources (conventional and nano) had a significant effect, with the Kt treatment recording a value of 5.289 kg m^{-3}, a 31% increase compared to the K0 treatment, which had the lowest value of 4.038 kg m^{-3}. The addition of potassium had a significant effect on increasing water use efficiency, and can be attributed to the role of potassium in mitigating most of the damage caused by water stress, allowing the plant to cope with drought and thereby increasing its water use efficiency. Potassium enhances the plant's ability to retain water and reduces transpiration rates, as it regulates transpiration and stomatal closure (4).

Regarding water stress levels, the highest value was 5.967 kg m^{-3} for I1, representing a 67.8% increase over the lowest value of 3.556 kg m^{-3} for I3. This may be attributed to reducing the amount of water added, thereby alleviating water stress levels I2 and I3, which in turn increased water use efficiency. The obtained results are consistent with those of (20). However, neither nano-silicon spraying nor binary nor triple interactions between the study factors had any significant effects, as indicated by the least significant difference (LSD) values.

Table 12: Effect of nano silicon and potassium on water use efficiency (kg m^{-3}) under water stress conditions.

Water stress	Silicon	Potassium				Interaction between water stress and silicon
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	
I1 (35% exhaustion)	Si_0 (0 ml l^{-1})	5.178	6.448	5.740	6.185	5.888
	Si_1 (4 ml l^{-1})	5.255	6.833	5.800	6.300	6.047
I2 (45% exhaustion)	Si_0 (0 ml l^{-1})	3.793	5.165	4.233	4.537	4.432
	Si_1 (4 ml l^{-1})	3.969	5.298	4.288	4.974	4.632
I3 (55% exhaustion)	Si_0 (0 ml l^{-1})	2.926	4.276	3.362	3.748	3.578
	Si_1 (4 ml l^{-1})	3.110	3.712	3.469	3.841	3.533
LSD at 0.05 for triple interference		NS				NS
Mean of Potassium		4.038	5.289	4.482	4.931	
LSD 0.05		0.1607				
Water stress X potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Water Stress
I1 (35% exhaustion)		5.216	6.640	5.770	6.242	5.967
I2 (45% exhaustion)		3.881	5.232	4.260	4.755	4.532
I3 (55% exhaustion)		3.018	3.994	3.416	3.794	3.556
LSD 0.05		NS				0.1485
Silicon X Potasium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Silicon
Si_0 (0 ml l^{-1})		3.965	5.296	4.445	4.823	4.632
Si_1 (4 ml l^{-1})		4.111	5.281	4.519	5.038	4.737
LSD 0.05		NS				NS

Potassium use efficiency (%): Table 13 shows the combined effect of silicon and nano potassium on potassium utilization efficiency under water stress conditions. The Kn2 potassium medium treatment significantly improved at 417.4%, the highest improvement among potassium media. For water stress levels, level I3 had the highest average value, at 256.6%, a 45% increase over level I2, which recorded the lowest value at 177.0%. For silicon spraying, Si1 significantly improved, increasing by 236.2%, a 20.4% increase over level Si0, which recorded a 196.2% increase. Silicon nanoparticles possess unique physicochemical properties that enable them to easily penetrate plant cells, primarily due to their high specific surface area. This property influences the growth and development of plant roots, stimulating the plant to absorb various nutrients, including potassium.

Regarding the binary interaction of water stress with potassium, the I3Kn2 treatment significantly outperformed the others at 520.2%, as the differences were significant for this interaction according to the values of the least significant difference. Regarding the binary interaction of potassium with silicon, the Kn1Si1 treatment significantly outperformed the others, recording the highest value of 449.0%. There were no significant differences in the binary interaction between water stress and silicon, and no significant effect was observed for the triple interaction among the study factors.

The significant increase in potassium utilization efficiency may be attributed to the positive contribution of potassium to improving plant morphological characteristics. It increases potato growth rate through cell elongation and division, providing optimal conditions for cell division through its influence on the mechanics of many vital plant processes such as respiration, carbon metabolism, water and nutrient absorption, and increased enzyme activity. This increases the dry matter yield of aerial parts and tubers, as well as the potassium concentration, thereby enhancing total potassium absorption and, consequently, improving fertilizer utilization efficiency.

As seen in the table, potassium utilization efficiency of the nano-source increased significantly compared to the traditional potassium source (potassium sulfate). As is well known, traditional potassium fertilizers contain particles larger than 100 nanometers, making them difficult for plants to absorb, thereby decreasing their efficiency. This makes them more susceptible to losses despite their high efficiency and ultimately reduces the efficiency of traditional potassium utilization. The superiority of the nano-source is because the size and composition of their active components lead to improving the efficiency of nutrient use due to the small size of its particles, which range between 1-100 nanometers, as well as its very high surface area (16).

Table 13: The effect of nano silicon and potassium on potassium use efficiency (%) under water stress conditions.

Water stress	Silicon	Potassium				Interaction between water stress and silicon
		K_0 (0 kg K_2O ha^{-1})	**K_t (300 kg K_2O ha^{-1})**	**Kn_1 (15 kg K_2O ha^{-1})**	**Kn_2 (30 kg K_2O ha^{-1})**	
I1 (35% exhaustion)	Si_0 (0 ml l^{-1})	0.0	51.80	345.2	403.6	200.2
	Si_1 (4 ml l^{-1})	0.0	60.10	432.6	427.2	230.0
I2 (45% exhaustion)	Si_0 (0 ml l^{-1})	0.0	48.20	287.5	267.4	150.8
	Si_1 (4 ml l^{-1})	0.0	52.00	395.5	365.7	203.3
I3 (55% exhaustion)	Si_0 (0 ml l^{-1})	0.0	37.60	412.4	500.8	237.7
	Si_1 (4 ml l^{-1})	0.0	43.30	518.9	539.6	275.4
LSD at 0.05 for triple interference		NS				NS
Mean of Potassium		0.0	48.80	398.7	417.4	
LSD 0.05		19.40				
Water stress X potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Water Stress
I1 (35% exhaustion)		0.0	56.00	388.9	415.4	215.1
I2 (45% exhaustion)		0.0	50.10	341.5	316.6	177.0
I3 (55% exhaustion)		0.0	40.40	465.6	520.2	256.6
LSD 0.05		35.01				23.82
Silicon X Potassium						
		K_0 (0 kg K_2O ha^{-1})	K_t (300 kg K_2O ha^{-1})	Kn_1 (15 kg K_2O ha^{-1})	Kn_2 (30 kg K_2O ha^{-1})	Means for Silicon
Si_0 (0 ml l^{-1})		0.0	45.90	348.4	390.6	196.2
Si_1 (4 ml l^{-1})		0.0	51.80	449.0	444.2	236.2
LSD 0.05		23.21				9.83

Conclusions

It is possible to mitigate the effect of water stress on potato crops when irrigated at a high-stress level, by depleting 45% of the available water, without affecting the yield and plant characteristics studied. This is achieved by adding potassium to the soil and spraying nano-silicon, allowing for a 10% savings in water usage. Using nano-potassium and conventional potassium resulted in significant increases in potato yield. Furthermore, applying nano-potassium significantly enhanced fertilizer use efficiency as it reduced the amount of conventional potassium fertilizer required to only 10% of the total.

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The authors declare no conflict of interest.

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References

1. Ali, N. S., Abdul-Wahab, A. A., and Hamad, S. R. (2014). Soil Fertility Book. Scientific Books House for Printing and Publishing. College of Agriculture. University of Baghdad.
2. Al-Sahaf, F. H. (1989). Applied Plant Nutrition. Dar Al-Hikma Press. Ministry of Higher Education and Scientific Research, University of Baghdad.

3. Altamimi, N. K., Alkobaisy, J. S., and Sallume, M. O. (2025). The role of bacillus mucilaginosus bacteria, mushroom farm residues, and mineral potassium in some characteristics of potato plants. IOP Conference Series: Earth and Environmental Science, 1449(1): 012099. DOI: 10.1088/1755-1315/1449/1/012099.
4. Ameen, M., Akhtar, J., Anwar-ul-Haq, M., Abbasi, G. H., Ali, M., Ali, Q., Zahra, S. N., Akhtar, T., and Ghafoor, I. (2024). Potassium in plants: possible functions, mechanisms and proteomics under abiotic environmental stress. In: Metals and Metalloids in Plant Signaling, Aftab, T., Springer Nature Switzerland, 73-110. https://doi.org/10.1007/978-3-031-59024-5_5.
5. Bdullah, M. M., Waraich, E. A., Ahmad, M., Hussain, S., and Djalovic, I. (2025). Improving soybean drought tolerance via silicon-induced changes in growth, physiological, biochemical, and root characteristics. *Plant Signaling and Behavior*, *20*(1): 2465232. https://doi.org/10.1080/15592324.2025.2465232.
6. Chada, S., Asiedu, S., and Ofoe, R. (2023). An overview of plant morpho-physiology, biochemicals, and metabolic pathways under water stress. Horticult Int J, 7(4): 115-125. https://doi.org/10.15406/hij.2023.07.00285.
7. Choi, I., Chun, J., Choi, H. S., Park, J., Kim, N. G., Lee, S. K., ... and Cho, K. (2020). Starch characteristics, sugars and thermal properties of processing potato (Solanum tuberosum L.) cultivars developed in Korea. American Journal of Potato Research, 97(3): 308-317. https://doi.org/10.1007/s12230-020-09779-z.
8. Emmerichs, T., Lu, Y. S., and Taraborrelli, D. (2024). The influence of plant water stress on vegetation–atmosphere exchanges: implications for ozone modeling. Biogeosciences. 21(14): 3251-3269. https://doi.org/10.5194/bg-21-3251-2024.
9. FAO. (2024). WaPOR Database Methodology: Water Productivity through Open access of Remotely sensed derived data - Version 3. Food and Agriculture Organization of the United Nations, Rome, Italy. Available at: https://www.fao.org/in-action/wapor.
10. Kekeli, M. A., Wang, Q., and Rui, Y. (2025). The role of nano-fertilizers in sustainable agriculture: Boosting crop yields and enhancing quality. Plants, 14(4): 554. https://doi.org/10.3390/plants14040554.
11. Marques, D. J., Bianchini, H. C., Maciel, G. M., de Mendonça, T. F. N., and Silva, M. F. E. (2022). Morphophysiological changes resulting from the application of silicon in corn plants under water stress. Journal of Plant Growth Regulation, 41(2): 569-584. https://doi.org/10.1007/s00344-021-10322-5.
12. Martin, H. W., and Sparks, D. L. (1983). Kinetics of nonexchangeable potassium release from two coastal plain soils. Soil Science Society of America Journal, 47(5): 883-887. https://doi.org/10.2136/sssaj1983.03615995004700050008x.
13. Richard, L. A. (1954). Diagnosis and improvement of saline and alkali soils. US Department of Agriculture. Agricultural Handbook No. 60, Washington DC, 7-53. DOI: 10.1097/00010694-195408000-00012.
14. Said, E. M., and Sallume, M. O. (2020). Effect of addition potassium and spray (Humic and Fulvic) acids application on some growth and yield characteristics of squash, Cucurbita pepo L. Biochemical and Cellular Archives, 20(1): 769-776. DOI: 10.35124/bca.2020.20.1.769.

15. Sheng, H., Ma, J., Pu, J., and Wang, L. (2018). Cell wall-bound silicon optimizes ammonium uptake and metabolism in rice cells. Annals of botany, 122(2): 303-313. https://doi.org/10.1093/aob/mcy068.
16. Singh, M. D. (2017). Nano-fertilizers is a new way to increase nutrients use efficiency in crop production. International Journal of Agriculture Sciences, ISSN, 9(7): 0975-3710.
17. Wei-min, D., Ke-qin, Z., Bin-wu, D. U. A. N., Cheng-xiao, S., Kang-le, Z., Run, C., and Jie-yun, Z. (2005). Rapid determination of silicon content in rice. Rice Science, 12(2): 145.
18. Weisany, W., Razmi, J., Eshaghabadi, A. H., and Pashang, D. (2024). Silicon nanoparticles (SiNP): A novel and sustainable strategy for mitigating environmental stresses in plants. Journal of Soil Science and Plant Nutrition, 24(2): 2167-2191. https://doi.org/10.1007/s42729-024-01790-1.
19. Yan, G., Huang, Q., Zhao, S., Xu, Y., He, Y., Nikolic, M., and Zhu, Z. (2024). Silicon nanoparticles in sustainable agriculture: synthesis, absorption, and plant stress alleviation. *Frontiers in Plant Science*, *15*: 1393458. https://doi.org/10.3389/fpls.2024.1393458.
20. Zargar, S. M., Mahajan, R., Bhat, J. A., Nazir, M., and Deshmukh, R. (2019). Role of silicon in plant stress tolerance: opportunities to achieve a sustainable cropping system. 3 Biotech, 9(3): 73. https://doi.org/10.1007/s13205-019-1613-z.
21. Zeng, Q., Xie, H., Zheng, S., Zhao, Y., Zhang, X., Zheng, Y., ... and Ma, B. (2025). Foliar Fertilization-Induced Rhizosphere Microbial Mechanisms for Soil Health Enhancement. *Agronomy*, *15*(12): 2837. https://doi.org/10.3390/agronomy15122837.