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Impact of Potassium Humate and Nano-Silica on Growth and Productivity of Some Wheat Varieties under Saline Conditions

Sobhy Gh. R. Sorour [1*], **Mahmoud A. Ayad** [2], **Ayman A. Ahmed** [1], **Mohamed I. A. Hinash** [1] and **Asmaa F. Badawy** [2]

[1]*Agronomy Department, Faculty of Agriculture, Kafrelsheikh University, Egypt*
[2]*Soils, Water and Environment Research Institute, Agriculture Research Center, Egypt*

SALINITY in soil and irrigation water represents a critical constraint for wheat production, adversely affecting growth, yield, and grain quality. Much genetic variability has been reported in bread wheat (*Triticum aestivum*, L.) for tolerance against salinity at different growth stages. Therefore, this field study evaluated the salinity tolerance of three Egyptian wheat cultivars (Misr1, Shandweel1, and Giza171) and the mitigating potentials of potassium humate (KH) soil application; and silica nanoparticles (Si-NPs) foliar spray against salinity stress. The experiment was set up in saline loamy sandy soil under drip irrigation at West-West El-Minia, Egypt (28.12°N, 30.01°E) during the 2020/21 and 2021/22 seasons. The experimental design used is a split-split plot with three replications where wheat cultivars were assigned to main plots, the KH rates (0, 5, and 10 kg fed^{-1}) to sub-plots, and Si-NPs concentrations (0,100, and 200 mg l^{-1}) to sub-sub-plots. Results showed that the wheat cultivar Misr1 significantly outperformed the other two cultivars in the number of spikes m^{-2}, grain number per spike, grain yield (2.685 and 2.812 t per feddan in both seasons), N and P uptake in grains, N use efficiency (NUE), N recovery, and productivity of irrigation water (PIW). The cultivar Giza171 had higher straw yield and K uptake. Soil application of KH caused a substantial increase in all studied parameters. As the rates of KH increased from 0 to 10 kg fed$^{-1,}$ significantly improved spike number m^{-2}, grain number spike^{-1}, 1000-grain weight, grain yield, straw yield, NPK uptake in grains and straw, protein content, N recovery%, and PIW. Applying 5 kg KH per feddan resulted in the highest grain yields of 2.675 and 2.908 tons per feddan in the two seasons, respectively. All the studied traits were significantly increased by increasing the concentration of Si-NPs in the foliar spray solution from 0 to 200 mg l^{-1}, with the highest rates producing the best results. The rate of 200 mg l^{-1} enhanced yield components such as spike number, grain number spike^{-1}, 1000-grain weight, and grain yield, reaching 2.691 t fed^{-1} and 2.919 t fed^{-1} in the two seasons. Also, Si-NPs increased N, P, and K uptake in grains and straw, protein content, NUE, N recovery, and PIW, demonstrating comprehensive positive effects on wheat performance and quality. The research recommends combining 10 kg KH fed^{-1} and 200 mg Si-NPs l^{-1} with the Misr1 cultivar for optimal wheat production (2.932 and 3.264 tons of grain per feddan) in saline soils under drip irrigation systems.

Keywords: Wheat cultivars, Saline soils, Potassium humate, Silica nanoparticles, Saline water.

1. Introduction

Wheat (*Triticum aestivum* L.) is one of the most important cereal food grain crops in the world. However, abiotic stresses significantly challenge its productivity, particularly soil salinity, which has become a serious environmental problem affecting crop growth and productivity worldwide. Wheat is particularly susceptible to salinity, which impairs nutrient availability and uptake, subsequently affecting yield and quality attributes such as protein content and NUE (Salem *et al*., 2017a; Shaban *et al*., 2012). It has been demonstrated that the use of certain compounds, such as KH and Si-NPs, can mitigate the adverse effects of salinity on plants and facilitate the cultivation of salt-tolerant wheat varieties. In this connection, the application of KH at rates of 4 and 8 kg feddan^{-1} has been shown to enhance nutrient absorption, particularly nitrogen (N), phosphorus (P), and potassium (K), contributing to improved growth parameters, yield and its components of wheat plants under saline conditions (Salem *et al*., 2017a). Benito *et al*. (2023) and Salem *et al*. (2017b) reported that it enhances the availability of essential nutrients and promotes root development, which is crucial for nutrient uptake. Furthermore, Shabana *et al*. (2023) and El-Etr and Hassan (2017) concluded that KH enhances soil structure, leading to improved water retention and microbial activity, which are essential for plant health, particularly in saline or nutrient-deficient environments. Si-NPs is known to buffer plants against the detrimental effects of salinity by enhancing photosynthesis and increasing antioxidant activity, which mitigates oxidative stress (Osman *et al*., 2017; Sakar and AlBakry, 2022). Research conducted by Salem *et al*. (2017a, 2017b)

*Corresponding author e-mail: sobhhysor@yahoo.com
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demonstrated that the combination of KH and Si-NPs enhanced the growth and yield components of wheat, thereby improving nitrogen utilization efficiency and enhancing irrigation water use efficiency. This particular combination proves especially beneficial, as it strengthens the physiological and biochemical processes crucial for plant stress tolerance, thus underscoring its significance in optimizing crop yields under water-limited conditions (Osman *et al*., 2017; Sakara and AlBakry, 2022). Many researchers (Nassar *et al*., 2024; Salem *et al*., 2017a; El-Etr and Hassan, 2017) found that the dual application of KH and Si-NPs significantly increased the uptake of N, P, and K, which are crucial for optimal yield production. Benito *et al*. (2023) and Shabana *et al*. (2023) concluded that KH improved root morphology that enhanced nutrient absorption, while Si-NPs contribute to mechanical plant stability and nutrient transport within the plant system. The dual application of KH and Si-NPs produced better vegetative growth, resulting in higher protein content in grains (Salem *et al*., 2017a; Salem *et al*., 2017b). Awwad *et al*. (2015) show that using KH in conjunction with reduced irrigation levels while maintaining optimal Si-NPs concentrations can substantially increase crop yields without incurring additional water costs.

Field studies in wheat cultivation regions in Egypt have exhibited that yield losses range from 20% to 60% under moderate to severe salinity conditions, highlighting the urgent need for salt-tolerant cultivars and improved management practices (El-Hendawy and Hassan,2017). Elhag (2023) evaluated ten Egyptian bread wheat varieties for salinity tolerance under normal and saline soil conditions in the North Delta region. Among the tested varieties, Misr 1 and Shandaweel 1 showed strong salinity tolerance with stable growth, yield, chlorophyll, and proline under stress. These varieties showed less reduction in yield attributes and physiological traits compared to more sensitive cultivars. Misr 1 and Shandaweel 1 are recommended for saline soils. Giza171 showed low reductions in grain yield under high salinity, categorizing them as highly tolerant (Ebaid *et al*., 2019). In certain wheat varieties, especially the Misr 1 variety under saline conditions, the application of KH at a rate of 6 kg per feddan with irrigation water enhanced physiological traits and grain yield (Eryan and Genedy, 2023).

This study aimed to minimize the harmful effects of salt stress on wheat by using KH with irrigation water and foliar spraying of Si-NPs to improve the growth, yield, yield attributes and nutrient profiles of wheat varieties under saline conditions and drip irrigation.

2. Materials and Methods

2.1. Location and Objective

During the winter growing seasons of 2020-2021 and 2021-2022, two field experiments were done on salty loamy sandy soils in West-West El-Minia, Egypt (28.12° N, 30.01° E). The goal was to discover how different amounts of KH and foliar spraying of Si-NPs affected the yield, yield characteristics, and chemical parameters of three wheat cultivars grown under drip irrigation.

2.2. Soil chemical properties

Before planting, soil samples were taken from experimental locations at 0 to 30 cm depths to check chemical characteristics using established methods (Table 1). We used the method published by Cottenie *et al*. (1982) to get the soil pH and the technique described by Page *et al*. (1982) to find the electrical conductivity (EC). The Walkley-Black technique determined how much organic matter was in the soil (SOM) (Jackson, 1973). Jackson's methodology (1973) was used to determine available nitrogen (N), phosphorus (P), and potassium (K). The total carbonates (CaCO3) were counted by using Piper's method from 1950. The chemical qualities of the irrigation water are found in Table 2.

Table 1. Chemical analysis of the experimental soil (0-30 cm) in the 2020/21 and 2021/22 seasons.

Season	pH (1:2.5)	EC (ds m^{-1})	Ca CO_3 (g kg^{-1})	OM (g kg^{-1})	Available (mg kg^{-1})		
					N	P	K
2020/21	8.12	10.38	1.55	1.89	35.34	3.39	113.1
2021/22	7.99	9.56	1.45	1.92	32.21	4.04	136.4

Table 2. Some chemical properties of irrigation water used in the 2020/21 and 2021/22 seasons.

Season	EC (dS m^{-1})	pH	SAR	Cations (meq l^{-1})				Anions (meq l^{-1})			
				Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	CO_3^{-}	HCO_3^{-}	Cl^{-}	SO_4^{-}
2020/21	3.15	7.73	5.70	8.91	6.30	16.20	1.20	-	3.11	20.92	8.58
2021/22	3.41	7.82	4.86	8.90	8.50	14.30	1.30	0.00	3.35	21.15	8.50

2.3. Content of KH and Si-NPs

The KH utilized in this study was chemically analyzed and found to contain (mg kg^{-1}): humic acid (75), K_2O (10), fulvic acid (4), and iron (2), with a near-neutral pH of 6.70. The Si-NPs material was obtained from the National Research Centre (NRC), Egypt. Its physicochemical properties were characterized by a specific surface area ranging from 300 to 330 m^2 g^{-1}, an acidic pH of 4.0–4.5, and a uniform mean particle diameter of approximately 10 nm.

2.4. Experimental treatment

The study included three factors: wheat varieties, soil application of KH compounds, and foliar spraying of Si-NPs. The experiment was conducted on three wheat varieties (Misr1, Shandweel1, and Giza171) approved by the Ministry of Agriculture and Land Reclamation. Soil application of KH at the rates of 5 and 10 kg per feddan in two equal portions was applied at sowing and 30 days after sowing as a fertigation with the drip irrigation system and omitted as a control. Foliar spraying with a solution of Si-NPs at the concentrations of 100 and 200 mg l^{-1} was done twice at 35 and 50 days after sowing, and water was used as a control treatment. An experimental plot of each variety was planted without nitrogen fertilization in each replication outside the experimental parameters to estimate N recovery% % and N efficiency.

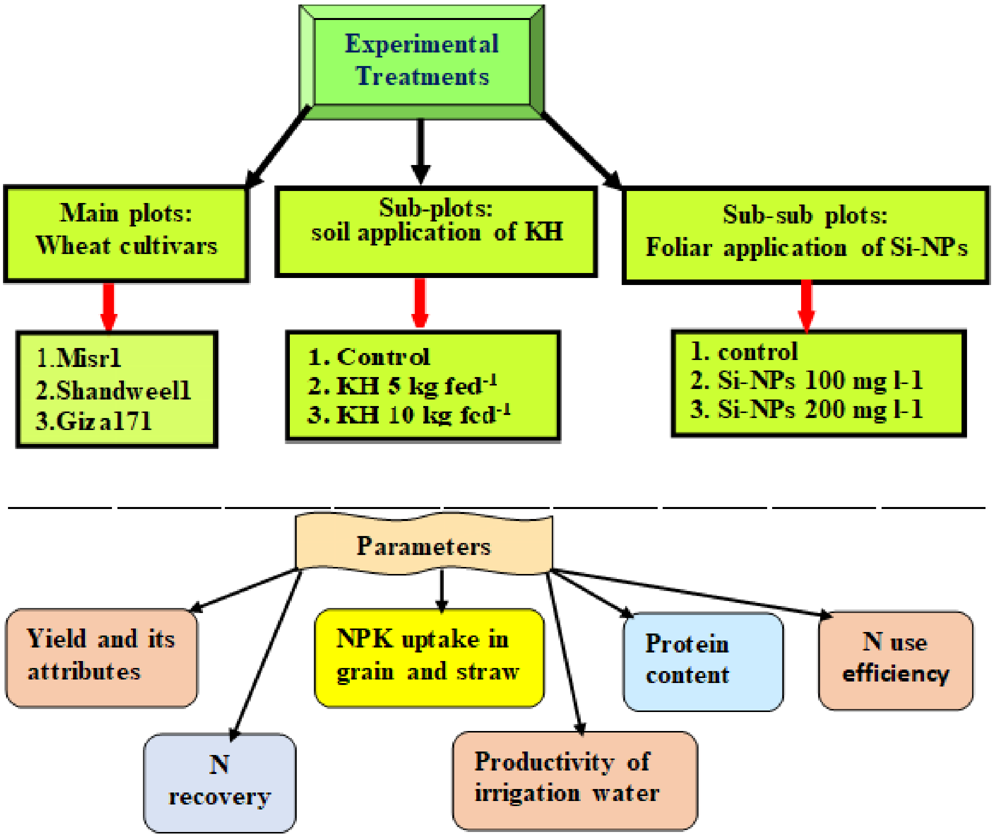

Fig. 1. The study flowchart.

2.5. Experimental design

The experiment design was a split-split plot in a randomized complete block design with three replications. The three wheat cultivars (Misr1, Shandweel1, and Giza171) were assigned to main plots, soil application of KH rates (0, 5, and 10 kg per feddan) to sub-plots and foliar spraying of Si-NPs concentrations (0, 100 and 200 mg l^{-1}) in sub-sub plots. The area of each sub-sub plot was 16 m^2 (4x4 m).

2.6. Agriculture practices

The seed of the three wheat cultivars was mechanically drilled in rows 20 cm apart and 3 cm deep with a rate of 50 kg seed $feddan^{-1}$ on November 15, 2020, and 2021 seasons. Each sub-subplot included 15 rows. The experiment area was irrigated with a surface drip irrigation system consisting of a main line, a sub-main line, and laterals. The dripper (GR type) has a 4L/h discharge rate at a spacing of 20 cm between drippers, 40 cm between lines, and a 33% leaching fraction. Phosphorus fertilizer at the rate of 30 kg P_2O_5 per feddan as phosphoric acid (85%), potassium fertilizer at the rate of 50 kg K_2O per feddan in the form of potassium sulfate (48-52% K_2O) was added in equal two doses with the sowing irrigation and at 30 days of sowing. However, N was applied as urea (46 % N) at 75 Kg N fed^{-1} in equal doses with irrigation water from the sowing to the tenth week in both seasons. The standard cultural practices for growing wheat in reclaimed soil were applied according to the recommendations of the Ministry of Agriculture. The harvest of wheat was done at 151 and 148 days after sowing at the first and second seasons, respectively.

2.7. Parameters

At harvest, the number of spikes m^{-2}, number of grains spike^{-1}, 1000-grain weight, grain yield fed^{-1}, and straw yield fed^{-1} were recorded according to the standard procedure. N, P, and K concentrations were determined in grains and straw samples on a dry weight basis according to Black (1965), and then N, P, and K uptake in grain and straw and grain protein content were calculated. N recovery% % and N use efficiency (NUE) in kg grain per kg N fertilizer were calculated according to **Crasswell and Godwin (1984)** as follows:

$$\text{N recovery\% \%} = \frac{\text{(N uptake in N fertilized plot- N uptake in the plot without N) X100}}{\text{(Quantity of N fertilizer applied in N fertilized plot)}}$$

$$\text{NUE (kg grain kg}^{-1}\text{ N)} = \frac{\text{(Grain yield in N fertilized plot- Grain yield in the plot without N)}}{\text{(Quantity of N fertilizer applied in N fertilized plot)}}$$

Productivity of irrigation water (PIW) was calculated by the formula (Michael, 1978):

$$\text{PIW (kg grain m}^{-3}\text{ water)} = \frac{\text{Grain yield (kg fed}^{-1}\text{)}}{\text{Applied irrigation water (m}^{3}\text{ fed}^{-1}\text{)}}$$

2.8. Statistical analyses

The obtained data were subjected to variance analysis according to Gomez and Gomez (1984). Treatment means were compared by Duncan's Multiple Range Test (Duncan, 1955). All statistical analysis was performed using the analysis of variance technique using the "MSTATC" computer software package.

3. Results

3.1. Grain yield and its attributes

The data in Table 3 reveal significant variations in agronomic performance (number of spikes m^{-2}, number of grains spike^{-1}, 1000-grain weight, grain yield, and straw yield) among the three wheat cultivars (Misr1, Shandweel1, and Giza171) in the two growing seasons. The wheat cultivar "Misr1" recorded the greatest spike number m^{-2} (459 and 465) in the two seasons, followed by Shandweel1 (448 and 457), while Giza171 had significantly lower spike numbers (424 and 431). Misr1 exceeded the other cultivars in the number of grains spike^{-1}, where it produced the highest number of grains spike^{-1} (64.1 and 60.9) in both seasons. However, the heaviest 1000-grain weight was produced from the Giza171cultivar (41.16 g) in the first season and the Misr1cultivar (42.22 g) in the second season, without significant differences in both seasons. Misr1 cultivar significantly outyielded the other two cultivars in grain yield per feddan in the two seasons. Misr1 cultivar produced the highest grain yield (2.685 and 2.812 t fed^{-1}) in both seasons. Giza171 and Shandweel1, being insignificant, produced higher straw yields than Misr1 in the first season. The differences among the three wheat cultivars in straw yield did not reach the level of significant in the second season. The data in Table 3 demonstrate the effects of different KH levels on various wheat yield parameters in the two seasons. Applying KH increased the number of spikes m^{-2}, number of grains spike^{-1}, 1000-grain weight, grain yield, and straw yield compared with the control treatment in both seasons. The 10 kg KH fed^{-1} recorded the highest values of all the mentioned traits in both seasons. The highest grain yields were observed at 10 kg fed^{-1}, with values of 2.675 and 2.908 t fed^{-1} in the two seasons, compared to the control treatment, which had grain yields of 2.301 and 2.434 t fed^{-1}.

Table 3. Number of spike m^{-2}, grain spike^{-1}, 1000-grain weight, grain yield, and straw yield of three wheat cultivars affected by KH and Si-NPs in 2020/21 and 2021/22 seasons.

Factor	Spikes (no m^{-2})		Grains (no spike^{-1})		1000-grain weight (g)		Grain yield (t fed^{-1})		Straw yield (t fed^{-1})	
	2020/21	2021/22	2020/21	2021/22	2020/21	2021/22	2020/21	2021/22	2020/21	2021/22
Cultivar (C):										
Misr1	459 a	465 a	64.1 a	60.9 a	40.68 ab	42.22 a	2.685 a	2.812 a	4.061 b	4.580 a
Shandweel1	448 a	457 a	62.3 ab	60.0 ab	39.15 b	40.64 b	2.451 b	2.622 ab	4.464 a	4.758 a
Giza171	424 b	431 b	61.5 b	58.6 b	41.16 a	41.37 ab	2.378 b	2.588 b	4.627 a	4.757 a
F-test	**	**	**	*	**	**	**	*	**	NS
KH, kg fed^{-1} (K):										
0	428 b	436 b	59.9 b	57.5 b	38.73 b	38.48 c	2.301 b	2.434 c	4.122 b	4.515 c
5	446 a	455 a	63.2 a	59.7 b	40.02 b	41.36 b	2.539 a	2.679 b	4.407 a	4.690 b
10	457 a	462 a	64.8 a	62.3 a	42.25 a	44.40 a	2.675 a	2.908 a	4.624 a	4.889 a
F-test	**	**	**	**	**	**	**	**	**	**
Si-NPs, mg l^{-1} (S):										
0	419 c	439 b	61.1 b	57.0 b	37.68 c	37.76 c	2.261 b	2.392 c	4.076 b	4.442 c
100	447 b	454 a	62.5 b	59.1 b	40.05 b	40.62 b	2.563 a	2.71 b	4.422 a	4.728 b
200	466 a	460 a	64.3 a	63.5 a	43.26 a	45.87 a	2.691 a	2.919 a	4.655 a	4.924 a
F-test	**	**	**	**	**	**	**	**	**	**
Interaction:										
CK	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
KS	*	*	**	*	*	*	*	*	NS	NS
CKS	NS	NS	NS	NS	NS	NS	*	*	NS	NS

*, ** and NS indicate $p < 0.05$, $p < 0.01$ and not significant, respectively. In each factor, means followed by a common letter are not significantly different at the 5% level according to Duncan's Multiple Range Test.

The data in Table 3 demonstrates the significant positive effects of Si-NPs application on yield and its components of wheat in two growing seasons. The highest concentration of Si-NPs (200 mg l^{-1}) excreted a marked increase in the number of spikes m^{-2}, number of grains spike^{-1}, 1000-grain weight, grain yield, and straw yield compared with the control treatment in the two seasons. Increasing Si-NPs concentration from 0 to 200 mg l^{-1} increases grain yield from 2.261 to 2.691 t fed^{-1} in the first season and 2.392 to 2.919 t fed^{-1} in the second.

Table 4. Number of spikes m^{-2}, number of grain spike^{-1}, 1000-grain weight, grain yield, and straw yield of three wheat cultivars, as affected by the interaction between KH and Si-NPs in 2020/21 and 2021/22 seasons.

KH (kg fed^{-1})	Si-NPs (mg l^{-1})	Spikes (no m^{-2})		Grains (no spike^{-1})		1000- grain weight (g)		Grain yield (t fed^{-1})	
		2020/21	2021/22	2020/21	2021/22	2020/21	2021/22	2020/21	2021/22
0	0	399 d	422 e	57.5 c	54.1 d	36.9 d	36.4 f	1.95 c	2.083 d
0	100	424 c	438 d	60.2 bc	56.8 cd	37.9 cd	38.3 e	2.386 b	2.509 c
0	200	459 ab	446 bcd	61.8 bc	61.4 abc	39.4 c	40.1 cd	2.565ab	2.71 bc
5	0	421 c	440 cd	62.2 ab	57.4 bcd	37.4 d	37.9 ef	2.291 b	2.447 c
5	100	452 b	459 ab	63 ab	58.8 bcd	39.5 c	40.9 bcd	2.591ab	2.732bc
5	200	464 ab	465 a	64.3 ab	62.8 ab	41.8 b	42.5 ab	2.734 a	2.856 b
10	0	434 c	455 abc	63.4 ab	59.4 bcd	39.1 cd	39.5 de	2.541ab	2.645bc
10	100	464 ab	463 a	64.1 ab	61.4 abc	42.3 ab	42 abc	2.711 a	2.888ab
10	200	473 a	468 a	66.7 a	66.1 a	44.2 a	43.7 a	2.773 a	3.19 a

In each column, means followed by a common letter are not significantly different at the 5% level according to Duncan's Multiple Range Test.

The interaction between KH and Si-NPs (KS) had a significant effect on grain yield and its components, except for straw yield in the two seasons (Table 3). The second-order interaction (CKS) had only a significant effect on grain yield in both seasons. The other interactions (CK and CS) did not affect all yields and their components in both seasons. Data in Table 4 showed that the number of spikes per m^2 generally increased with increasing both KH and Si-NPs in the two seasons. The combination of 10 kg KH fed^{-1} with 200 mg Si-NPS l^{-1} produced the highest number of spike m^{-2} (473 and 468) in both seasons. A similar trend was observed for the number of grains per spike. The combination of 10 kg fed^{-1} KH and 200 mg l^{-1} Si-NBs resulted in the highest number of grains per spike (66.7 and 66.1) in both seasons. The 1000-grain weight was markedly increased with increasing K humate and Si-NPs levels. The highest values were recorded at the maximum application rates (10 kg fed^{-1} K humate and 200 mg l^{-1} Si-NPs), reaching 45.2 g in the first and 51.0 g in the second season. Grain yield exhibited a consistent positive response to the combined application of K humate and Si-NPs. The highest yields were achieved with 10 kg fed^{-1} KH and 200 mg l^{-1} Si-NPs, producing 2.773 t and 3.190 t fed^{-1} in both seasons, respectively. The data in Table 5 illustrate the interaction CKS effect on grain yield in the two seasons. The response of three wheat cultivars significantly varied in grain yield at any combination of KH and Si-NPs, where the Misr1 cultivar outyielded the Shandweel1 *and* Giza171 cultivars. The wheat cultivar “Misr1” received 10 kg KH fed^{-1}+ 200 mg Si-NPs l^{-1} achieved the highest yield (2.932 and 3.264 t fed^{-1} in the first and second season, respectively), while Giza171 yielded only 2.667 and 3.216 t fed^{-1} at the same treatment condition.

3.2. NPK uptake

Table 6 presents nitrogen (N), phosphorus (P), and potassium (K) uptake (kg fed^{-1}) in both grains and straw of three wheat cultivars (Misr1, Shandweel1, and Giza171) as affected by KH and Si-NPs applications across two growing seasons. The three cultivars markedly varied in NPK uptake in grains and straw (kg fed-1) in both seasons. The wheat cultivar Misr1 achieved the highest grain uptake of nitrogen (50.12 and 51.24 kg N fed^{-1}) and phosphorus (15.96 and 17.53 kg P fed^{-1}) compared with the Shandweel1 cultivar in both seasons. The cultivar Giza171 did not differ in P uptake in grain in the second season. Giza171 cultivar recorded higher K uptake in grains (18.61 and 19.92 kg fed^{-1}) than Misre1 in the two seasons. The maximum values of NPK uptake in straw were recorded in the cultivar Giza171 compared with the cultivar Misr1 in both seasons.

Table 5. Grain yield of wheat, as affected by the interaction among cultivar, KH, and Si-NPs in 2020/21 and 2021/22 seasons.

KH (kg fed^{-1})	Si-NPs (mg l^{-1})	2020/21 season			2021/22 season		
		Misr1	Shandw.1	Giza171	Misr1	Shandw.1	Giza171
0	0	2.284 o	1.975 r	1.590 s	2.172 q	2.106 r	1.971 s
0	100	2.506 j	2.289 o	2.362 n	2.553 l	2.530 m	2.443 o
0	200	2.750 d	2.481 k	2.465 kl	2.941 de	2.635 ij	2.556 l
5	0	2.392 m	2.257 p	2.223 q	2.529 m	2.444 o	2.370 p
5	100	2.774 c	2.514 j	2.484 k	2.927 e	2.651 i	2.618 j
5	200	2.922 a	2.689 f	2.590 h	3.092 c	2.777 g	2.698 h
10	0	2.704 ef	2.467 kl	2.453 l	2.868 f	2.594 k	2.473 n
10	100	2.900 b	2.667 g	2.565 i	2.955 d	2.768 g	2.943 de
10	200	2.933 a	2.719 e	2.667 g	3.265 a	3.090 c	3.217 b

In each season, means followed by a common letter are not significantly different at the 5% level according to Duncan's Multiple Range Test.

Foliar spraying with Si-NPs greatly increased the uptake of nitrogen that both grains and straw (Table 6). The greatest N uptake was 52.33 and 54.85 kg fed^{-1} in grain N; 38.60 and 44.05 kg fed^{-1} in straw at 200 mg Si-NPs l^{-1}. Compared to the control (0 mg Si-NPs l^{-1}), this means that grain N uptake goes higher by around 32% and 38% and straw N uptake goes up by 36% and 20%. As the rate of Si-NPs used on the plants increased, the amount of P they took up also went up. At 200 mg Si-NPs l^{-1}, the maximum P uptake was observed. This was 33% and 29% higher for grain P uptake and 31% and 20% higher for straw P uptake than the control. The use of Si-NPs also greatly increased K uptake, with the maximum levels seen at 200 mg Si-NPs l^{-1} (20.25 and 22.38 kg fed^{-1} for grain K uptake; 68.96 and 72.49 kg fed^{-1} for straw K uptake). Compared to the control, there is around a 30% and 35% increase in grain K uptake and a 29% and 26% increase in straw K uptake.

The data in Table 6 reveal consistent patterns of enhanced NPK uptake in grain and straw with increasing KH application rates from 0 to 10 kg KH fed^{-1} in both seasons. The soil application of KH resulted in a significant increase in N, P and K uptake in wheat grains and straw compared with the control treatment in the two growing seasons. N uptake in grains was increased from 39.71-40.32 kg fed^{-1} at 0 kg KH fed^{-1} (control) to 52.51-54.97 kg fed^{-1} at 10 kg KH fed^{-1} in the two seasons, while N uptake in straw was similarly increased from 29.99-37.35 kg fed^{-1} to 37.62-44.06 kg fed^{-1}. The rate of 10 kg KH fed^{-1} increased N uptake in grains by 32-36%, P uptake by 25-26%, and K uptake by 20-26% compared to the control treatment. The same trend was found in NPK uptake in straw.

Table 6. NPK uptake (kg fed^{-1}) in grains and straw of three wheat cultivars affected by KH and Si-NPs in 2020/21 and 2021/22 seasons.

Factor	Grains						Straw					
	N uptake (kg fed^{-1})		P uptake (kg fed^{-1})		K uptake (kg fed^{-1})		N uptake (kg fed^{-1})		P uptake (kg fed^{-1})		K uptake (kg fed^{-1})	
	2020/21	2021/22	2020/21	2021/22	2020/21	2021/22	2020/21	2021/22	2020/21	2021/22	2020/21	2021/22
Cultivar (C):												
Misr1	50.12 a	51.24 a	15.96 a	17.53 a	17.66 b	19.28 b	31.03 b	37.68 b	4.76 c	6.33 b	47.28 b	61.92 b
Shandweel1	45.58 b	46.22 b	14.38 b	15.76 b	17.74 b	19.67 ab	31.61 b	41.88 ab	6.12 b	7.06 ab	65.12 a	66.39 a
Giza171	44.17 b	46.25 b	14.86 b	17.10 a	18.61 a	19.92 a	38.87 a	42.25 a	7.29 a	7.73 a	71.35 a	68.90 a
F-test	**	*	*	**	*	*	*	*	**	*	*	*
KH, kg fed^{-1} (K):												
0	39.71 b	40.32 b	13.30 b	14.90 b	16.2 b	17.36 b	29.99 b	37.35 b	5.51 b	6.59 b	56.85 b	59.81 b
5	47.64 a	48.42 a	15.22 ab	16.71 ab	18.35 ab	19.72 ab	33.91 ab	40.40 ab	6.08 a	6.90 ab	61.54 ab	65.83 ab
10	52.51 a	54.97 a	16.68 a	18.78 a	19.46 a	21.80 a	37.62 a	44.06 a	6.58 a	7.62 a	65.36 a	71.57 a
F-test	*	*	*	**	**	*	**	**	*	*	*	**
Si-NPs, mg l^{-1} (S):												
0	39.65 b	39.76 b	12.85 c	14.66 c	15.53 c	16.6 c	28.29 b	36.71 b	5.26 b	6.34 b	53.63 b	57.54 b
100	47.88 a	49.10 a	15.23 b	16.83 b	18.24 b	19.89 b	34.64 a	41.04 a	6.04 ab	7.16 a	61.16 ab	67.19 a
200	52.33 a	54.85 a	17.12 a	18.90 a	20.25 a	22.38 a	38.60 a	44.05 a	6.87 a	7.62 a	68.96 a	72.49 a
F-test	**	**	*	**	**	**	**	**	*	*	**	**
Interaction:												
CK	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
KS	**	**	**	**	**	**	**	**	*	*	*	**
CKS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

*, ** and NS indicate $p < 0.05$, $p < 0.01$ and not significant, respectively. In each factor, means followed by a common letter are not significantly different at the 5% level according to Duncan's Multiple Range Test.

All the first and second order interactions did not significantly affect NPK uptake in grains and straw, except the interaction of KS in both seasons (Table 6). The interaction of KH and Si-NPs (KS) had a significant effect on N, P and K uptake in grains and straw in favour of the rate of 10 kg fed^{-1} KH combined with 200 mg l^{-1} Si-N compared with the control treatment in both seasons (Table 7). The highest N uptake (55.9 kg fed^{-1} and 63.16 kg fed^{-1} in grains and 41.81 and 47.82 kg fed^{-1} in straw) was observed with the application of 10 kg fed^{-1} KH combined with 200 mg l^{-1} Si-NPs, which reaching 55.9 kg fed^{-1} and 63.16 kg fed^{-1} in grains and 41.81 and 47.82 kg fed^{-1} in straw in both seasons, respectively. This represents an 84.2% and 100.4% increase in grains and 75.2% and 42.0% in straw over the control treatment in the respective seasons. P uptake followed a similar trend, with the highest values (18.32 and 21.03 kg fed^{-1} in grain and 7.33 and 8.33 kg fed^{-1} in straw) recorded at the highest rates of both KH and Si-NPs. This represents a 74.6% and 70.1% increase in grain and 7.33 and 8.33 kg fed^{-1} in straw over the control for both seasons. K uptake reached maximum values of 21.18 and 25.18 kg fed^{-1} in grains and 72.69 and 77.49 kg fed^{-1} in straw, with the highest application rates of both amendments in the two seasons. This represents increases of 64.7% and 76.5% in grain and 47.1% and 50.1% in straw compared to the control.

Table 7. NPK uptake (kg fed^{-1}) in grains and straw affected by the interaction of cultivar, KH, and Si-NPs in 2020/21 and 2021/22 seasons.

KH (kg fed^{-1})	Si-NPs (mg l^{-1})	Grains						Straw					
		N uptake (kg fed^{-1})		P uptake (kg fed^{-1})		K uptake (kg fed^{-1})		N uptake (kg fed^{-1})		P uptake (kg fed^{-1})		K uptake (kg fed^{-1})	
		2020/21	2021/22	2020/21	2021/22	2020/21	2021/22	2020/21	2021/22	2020/21	2021/22	2020/21	2021/22
0	0	30.34 d	31.51 f	10.49 f	12.36 e	12.86 g	14.27 f	23.87 f	33.68 f	4.43 d	5.97 f	49.4 d	51.64 f
0	100	40.90 c	42.30 e	13.78 e	15.01 d	16.7 e	18.12 d	30.39 de	37.20 e	5.62 c	6.69 de	56.31 cd	60.24 de
0	200	47.79 b	47.17 d	15.82 cd	17.31 c	19.09 bc	19.97 c	35.49 bc	41.14 cd	6.34 abc	7.06 bcd	64.68 abc	67.36 c
5	0	40.31 c	40.21 e	13.11 e	14.87 d	15.87 f	16.90 e	28.29 e	36.50 e	5.57 c	6.28 ef	53.62 cd	56.87 e
5	100	49.58 b	50.79 c	15.34 d	16.83 c	18.50 c	20.02 c	35.10 bc	41.57 cd	5.98 bc	7.04 bcd	61.54 abc	68.00 c
5	200	53.20 a	54.17 b	17.31 b	18.34 b	20.54 a	22.01 b	38.62 ab	43.20 bc	6.87 ab	7.47 bc	69.48 ab	72.41 b
10	0	48.20 b	47.36 d	15.16 d	16.56 c	17.7 d	18.66 d	32.67 cd	39.98 d	5.92 bc	6.87 cde	57.82 bcd	64.14 cd
10	100	53.18 a	54.46 b	16.56 bc	18.64 b	19.38 b	21.52 b	38.47 ab	44.48 b	6.53 abc	7.64 b	65.52 abc	73.16 b
10	200	55.9 a	63.16 a	18.32 a	21.03 a	21.18 a	25.18 a	41.81 a	47.82 a	7.33 a	8.33 a	72.69 a	77.49 a

In each column, means followed by a common letter are not significantly different at the 5% level according to Duncan's Multiple Range Test.

3.3. Protein content

Protein content in grains of three wheat cultivars as affected by KH and Si-NPs during two seasons is presented in Table 8. The protein content of wheat grains is a crucial quality parameter for various end-use applications. There was no significant difference in protein content among the three wheat cultivars (Misr1, Shandweel1, and Giza171) in both seasons. The soil application of KH exerted a significant increase in protein content compared with the control treatment in both seasons. The highest protein content was observed with 10 kg KH fed-1 (12.26% and 11.78% in both seasons), which was statistically similar to the 5 kg KH fed-1 treatment but significantly higher than the control. Foliar application of Si- NPs also significantly increased protein content. The 200 mg Nano-Si l^{-1} treatment resulted in the highest protein content (12.14% and 11.7%) in the two seasons, statistically similar to the 100 mg Si-NPs l^{-1} treatment but significantly higher than the control. The effect of interaction between KH and Si-NPs (KS) on protein content in wheat grain was significant in both seasons (Table 8). Figure 2 showed that protein content in grains increased incrementally with increasing rates of both KH and Si-NPs in both seasons. The highest values of protein content (12.37% and 12.63 %) were achieved at 10 kg KH fed^{-1} + 200 mg Si-NPs l^{-1}. Soil application of 10 kg KH fed^{-1} alone increased protein content to 11.90–11.17%, while foliar spraying with 200 mg Si-NPs l^{-1} alone increased protein content to 11.60–10.83%. The control treatment without KH and Si-NPs produced the lowest protein content (9.70-9.43%) in both seasons. Applying Si-NPs alone at 200 mg l^{-1} increased protein content by 19.6-14.8.1% than the control in the two seasons. KH application at 10 kg fed^{-1} without Si-NPs elevated protein content to 11.90-11.17%. However, the combination of 10 kg KH fed^{-1} + 200 mg Si-NPs l^{-1} achieved peak protein values of 12.37-12.63%, representing a 31.2-32.6% increase over control.

3.4. Nitrogen use efficiency (NUE)

Data in Table 8 show that the three cultivars significantly varied in NUE (kg grain kg^{-1} N) in the first season only. Misr1 outperformed others in NUE (27.63 kg grain/kg N), while Giza171 produced lower NUE (23.72 kg grain/kg N) in the first season. NUE was improved by increasing soil application of the KH rate from 0 to 10 kg fed^{-1} in both seasons (Table 8). NUE peaked at 10 kg KH (27.64 and 30.96 kg grain/kg N in the two seasons). The highest rate of Kh increased NUE by 22.1 to 25.6 % compared with the control treatment in both seasons. Foliar application of Si- NPs significantly increased protein content in grains. Foliar spraying with the 200 mg Si-NPs l^{-1} resulted in the highest NUE (27.85 and 31.11 kg grain/kg N in 2020/21 and 2021/22, respectively), which was statistically similar to the 100 mg Si-NPs l^{-1} treatment but significantly higher than the control.

Table 8. Protein content in grains, N use efficiency (kg grain/kg N), and N recovery (%) with grain and productivity of irrigation water (kg grain per m^3 water applied) for three wheat cultivars affected by KH and Si-NPs in 2020/21 and 2021/22 seasons.

Factor	Protein (%)		N efficiency (kg grain/kg N)		N recovery (%)		Water productivity (kg m^{-3})	
	2020/21	2021/22	2020/21	2021/22	2020/21	2021/22	2020/21	2021/22
Cultivar (C):								
Misr1	11.60 a	11.32 a	27.63 a	29.82 a	59.87 a	61.19 a	1.35 a	1.36 a
Shandweel1	11.55 a	10.94 a	24.75 ab	27.19 a	54.34 b	54.64 b	1.23 b	1.27 ab
Giza171	11.49 a	11.06 a	23.72 b	26.49 a	52.50 b	54.53 b	1.20 b	1.26 b
F-test	NS	NS	*	NS	**	**	**	**
K humate, kg fed^{-1} (K):								
0	10.69 b	10.28 b	22.64 b	24.64 b	46.35 b	46.67 b	1.16 b	1.18 c
5	11.70 a	11.25 a	25.82 ab	27.90 ab	56.93 a	57.47 a	1.27 a	1.3 b
10	12.26 a	11.78 a	27.64 a	30.96 a	63.43 a	66.21 a	1.34 a	1.41 a
F-test	**	**	*	*	**	**	**	**
Si-NPs, mg l^{-1} (S):								
0	10.86 b	10.31 b	22.11 b	24.08 b	46.27 b	45.93 b	1.14 b	1.16 c
100	11.65 a	11.3 a	26.14 a	28.32 a	57.25 a	58.38 a	1.29 a	1.32 b
200	12.14 a	11.7 a	27.85 a	31.11 a	63.19 a	66.05 a	1.35 a	1.42 a
F-test	**	**	**	*	**	**	**	*
Interaction:								
CK	NS	NS	NS	NS	NS	NS	NS	NS
CS	NS	NS	NS	NS	NS	NS	NS	NS
KS	**	**	**	**	**	**	**	**
CKS	NS	NS	NS	NS	NS	NS	**	**

*, ** and NS indicate $p < 0.05$, $p < 0.01$ and not significant, respectively. In each factor, means followed by a common letter are not significantly different at the 5% level according to Duncan's Multiple Range Test.

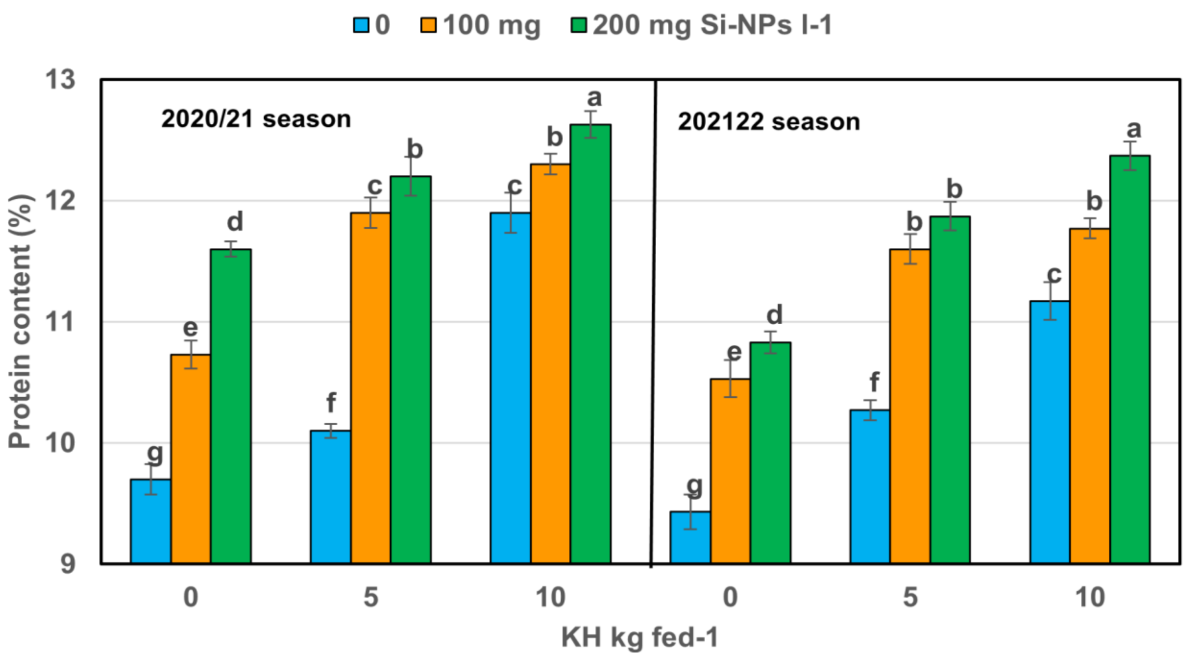

Fig. 2. Protein content in grains as affected by the interaction between KH **and** Si-NPs **in the 2020/21 and 2021/22 seasons.**

The most interactions among cultivars (C) and KH or Si-NPs (CK, CS and CKS) had no significant effect on NUE (kg grain/kg N) in both seasons (Table 8). However, the interaction between KH and Si-NPs (KS) markedly affected NUE in the two seasons. Figure 3 shows that combined treatments substantially improved NUE (kg grain/kg N). The highest N efficiency (29.00 and 34.67 kg grain/kg N in 2020/21 and 2021/22, respectively) was recorded with the maximum application rates of both amendments.

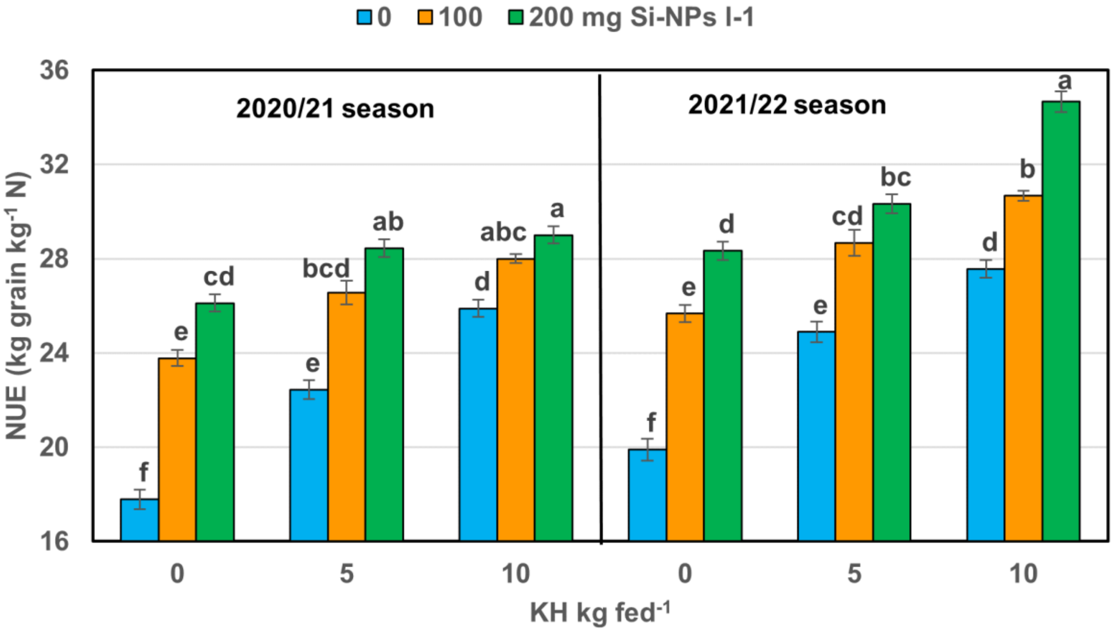

Fig. 3. N use efficiency (NUE) as affected by the interaction between KH and Si-NPs in the 2020/21 and 2021/22 seasons.

3.5. Nitrogen recovery (%)

Data in Table 8 showed that the three wheat cultivars markedly varied in N recovery % in both seasons. Misr1's superior N recovery (59.87% and 61.19% in both seasons) contrasted with Giza171's lower N recovery (52.50% and 54.53%). Soil application of KH resulted in a significant increase in N recovery % compared with the control treatment in both seasons. The highest values of N recovery (63.19 and 66.05 % in both seasons) were observed with the application of 10 kg KH fed^{-1}. There were no significant differences in N recovery % between 5 and 10 kg KH fed^{-1} in the two seasons. Foliar spray of Si-NPs also pronouncedly improved N recovery %. N recovery % was significantly increased by increasing Si-NP concentration from 0 to 200 mg l^{-1} in the two seasons. The 200 mg Nano-Si l^{-1} treatment resulted in the highest N recovery (63.19% and 66.05% in the two seasons). The interaction between KH and Si-NPs (KS) significantly affected N recovery % in both seasons (Table 8). Figure 4 demonstrates that the combination of KH and Si-NPs significantly improved nitrogen recovery in wheat grain in the two seasons. N recovery% was increased dramatically with each increment of KH or Nano-Si at the same rate as other materials in both seasons. Nitrogen recovery percentage followed a similar trend of NUE, with the highest values (68.22% and 77.22% in both seasons) observed with the maximum application rates (10 kg KH +200 mg Nano-Si). All other interactions had no significant effect on N recovery% in both seasons.

Productivity of irrigation water (PIW)

PIW in kg grain per m^3 water represents the efficiency with which irrigation water is converted to grain yield. Data in Table 8 show that the cultivar Misr1 was superior PIW (1.35 and 1.36 kg grain m^{-3} water) compared to Shandweel1 (1.23 and 1.27 kg m^{-3}) and Giza171 (1.20 and 1.26 kg m^{-3}) in both seasons. The application of KH resulted in a significant increase in PIW compared with control treatment in both seasons (Table 8). In the first season, applying 10 kg fed^{-1} of KH increased WP to 1.34 kg m^{-3} compared to 1.16 kg m^{-3} in the control treatment. Similarly, in the second season, the highest rate of KH application (10 kg fed^{-1}) yielded a maximum WP of 1.41 kg m^{-3}. PIW was significantly increased by foliar spraying with Si-NPs compared with water as a control in both seasons. In the first season, PIW increased from 1.14 kg m^{-3} in the control to 1.35 kg m^{-3} with 200 mg l^{-1} Si-NPs. In the second season, the corresponding values were 1.16 kg m^{-3} and 1.42 kg m^{-3}.

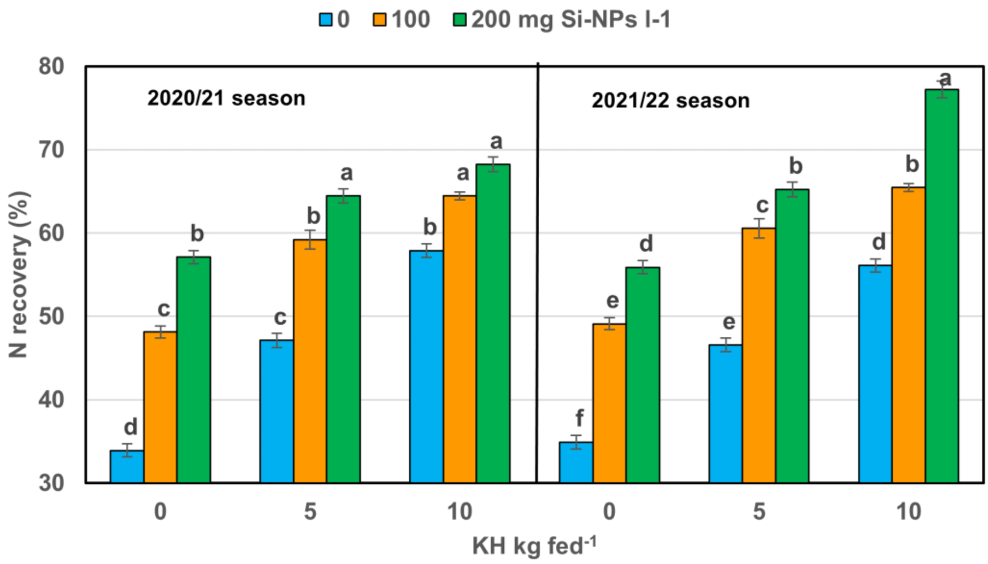

Fig. 4. N recovery (%) with grain as affected by the interaction between KH **and** Si-NPs **in the 2020/21 and 2021/22 seasons.**

Data in Table 8 show that the significant interactions (KS) between KH and Si-NPs and the three-way interaction (CKS) among cultivar, KH and Si-NPs in both seasons indicate that the combined application of these amendments produces synergistic effects on the productivity of irrigation water (PIW). Figure 5 shows that increasing the rates of KH and Si-NPs significantly increased PIW in both seasons. The combination of 10 kg KH fed^{-1} and 200 mg Si-NPs l^{-1} achieved the highest PIW (1.39 and 1.55 kg grain m^{-3} water in the two seasons, respectively). This combination increased PIW by approximately 42% in the first and 53% in the second seasons compared to the control. The second-order interaction among cultivars, KH, and Si-NPs (CKS) in both seasons indicates that the combined application of these amendments produces synergistic effects on the productivity of irrigation water (Table 8). The data in Table 9 shows consistent differences in water productivity among the three wheat cultivars. Misr1 recorded the highest PIW, followed by Shandaweel1 and Giza171, generally showing the lowest values at the most combinations of KH and Si-NPs in both seasons. Increasing KH application rates from 0 to 10 kg fed^{-1} significantly improved irrigation water productivity across all cultivars. Si-NPs application showed an apparent dose-dependent positive effect on water productivity. The highest concentration (200 mg Si-NPs l^{-1}) consistently produced the best results across all cultivars and KH levels. The most striking results came from combined treatments. The wheat cultivar Misr1, which received 10 kg fed^{-1} KH and 200 mg l^{-1} Si-NPs, recorded the highest values of PIW (1.47 and 1.58 kg grain m^{-3} water in both seasons).

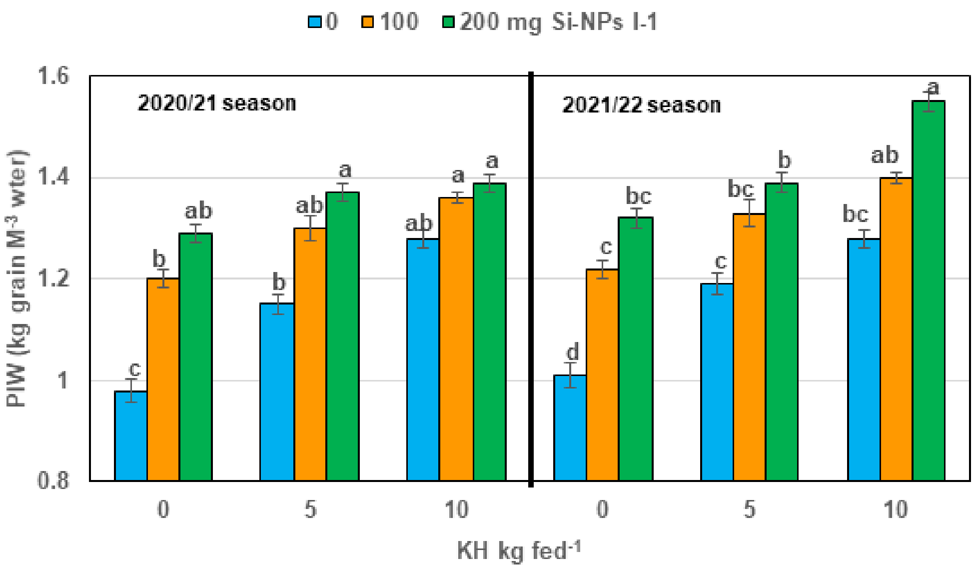

Fig. 5. Productivity of irrigation water (PIW) as affected by the interaction between KH **and** Si-NPs **in the 2020/21 and 2021/22 seasons.**

Table 9. Productivity of irrigation water (kg grain m^{-3} water) of wheat, as affected by the interaction of cultivars, KH, and Si-NPs in 2020/21 and 2021/22 seasons.

KH (kg fed^{-1})	Si-NPs (mg l^{-1})	2020/21 season			2021/22 season		
		Misr1	Shandw.1	Giza171	Misr1	Shandw.1	Giza171
0	0	1.15 o	0.99 r	0.8 s	1.05 q	1.02 r	0.96 s
0	100	1.26 j	1.15 o	1.19 n	1.24 l	1.23 m	1.19 o
0	200	1.38 d	1.24 k	1.24 kl	1.43 de	1.28 ij	1.24 l
5	0	1.2 m	1.13 p	1.12 q	1.23 m	1.19 o	1.15 p
5	100	1.39 c	1.26 j	1.25 k	1.42 e	1.29 i	1.27 j
5	200	1.47 a	1.35 f	1.3 h	1.5 c	1.35 g	1.31 h
10	0	1.36 ef	1.24 kl	1.23 l	1.39 f	1.26 k	1.2 n
10	100	1.46 b	1.34 g	1.29 i	1.43 d	1.34 g	1.43 de
10	200	1.47 a	1.36 e	1.34 g	1.58 a	1.5 c	1.56 b

In each season, means followed by a common letter are not significantly different at the 5% level according to Duncan's Multiple Range Test.

4. Discussion

The current study demonstrated significant variation among the three wheat cultivars (Misr1, Shandweel1, and Giza171) in their growth, yield, and nutrient utilization efficiency under saline soil conditions, with clear differences in adaptation strategies. Misr1 consistently demonstrated superior performance by producing the highest spike density, grains per spike, and grain yield, supported by its greater nitrogen (N) and phosphorus (P) uptake in grains, efficient redistribution of N from vegetative tissues, higher nitrogen use efficiency (NUE), recovery percentage, and irrigation water productivity (PIW). These reflect its optimized genetic architecture for productive tillering, grain filling, and efficient resource utilization, thereby confirming its greater tolerance to salinity stress and superior adaptability (Elhag, 2023; El-Khamissy *et al*., 2023; Megahed *et al*., 2022; Yokamo *et al*., 2023; Congreves *et al*., 2024; Tadesse and Asefa, 2025). Shandweel1 showed intermediate performance with stable physiological traits and yield response under stress. On the other hand, Giza171 was good at accumulating biomass since it produced the most straw and took up the most potassium (K), but it was less efficient at moving nitrogen back to grains, which led to decreased grain production (Todeschini *et al*., 2016; Benchelali *et al*., 2022; Elhag, 2023). These findings are consistent with earlier reports that Misr1 and Shandweel1 are more salt-tolerant Egyptian wheat cultivars with stable yield performance under saline conditions (Ebaid *et al*., 2019; Elhag, 2023; El-Hendawy and Hassan, 2017; Salem *et al*., 2017a; Osman *et al*., 2017). Therefore, Misr1 is strongly recommended for wheat cultivation systems under saline conditions due to its balanced combination of high grain yield, NUE, and water productivity, confirming its agricultural and physiological superiority (Elhag, 2023; Eryan and Genedy, 2023).

The soil application of KH containing 75 mg humic acid, 10 mg K_2O, 4 mg fulvic acid, and 2 mg iron per kg significantly enhanced all studied wheat growth parameters under saline soil conditions, such as spike number, grain number per spike, 1000-grain weight, grain yield, straw yield, and nutrient uptake (N, P, K). KH increased spike density and grain number, directly improving yields, especially at the highest application rate of 10 kg fed^{-1}. It also enhanced NUE and N recovery percentage, optimizing nitrogen uptake and utilization under salinity stress. Protein content in wheat grains was improved by KH, indicating enhanced grain quality. Moreover, KH improved the productivity of irrigation water (PIW), thus enabling wheat to use more efficiently under saline conditions. The humic acid component of KH enhances soil structure and microbial activity, boosting nutrient availability and uptake (El-Etr and Hassan, 2017; Shabana *et al*., 2023). Potassium and fulvic acid in KH play important nutritional roles, enhancing N, P, and K uptake and supporting growth and salinity tolerance (Salem *et al*., 2017a; Benito *et al*., 2023). The iron content aids physiological functions under salinity stress. KH and Si-NPs combined have synergistic benefits, further improving wheat growth, yield, and nutrient use efficiency under salinity (Salem *et al*., 2017a; Osman *et al*., 2017).

Foliar spraying with Si-NPs under saline conditions increased spikes m^{-2}, grains $spike^{-1}$, 1000 grain weight, grain and straw yield. The highest rate of Si-NPs (200 mg l^{-1}) produced the greatest gains in both seasons; for example, grain yield rose from 2.261 to 2.691 t fed^{-1} in the first season and from 2.392 to 2.919 t fed^{-1}, in the second season. These positive effects aligned with prior evidence that nano silica improves yield components in salt-affected wheat via better ion balance and growth physiology (Ayman *et al*., 2020; Salem *et al*., 2017a). Si-NPs significantly boosted the uptake of nitrogen, phosphorus, and potassium in both grains and straw, peaking at

200 mg l^{-1}, indicating improvements of 30–38% compared to control and aligning with findings that foliar nano-silica promotes nutrient absorption while reducing sodium accumulation in saline conditions (Ayman *et al*., 2020; Ali *et al*., 2023). Protein content in grains rose significantly with Si-NPs, peaking at 200 mg l−1200mg l^{-1} (12.14% and 11.7%), in line with the role of nano-silicon in strengthening N assimilation and metabolic activity under salt stress (Salem *et al*., 2017a; Osman *et al*., 2017). Nitrogen use efficiency and N recovery also improved steadily with Si-NP dose, reaching 27.85 and 31.11 kg grain kg^{-1} N for NUE and 63.19% and 66.05% for N recovery at 200 mg l^{-1} across the two seasons, corroborating that nano-silica facilitates N uptake and utilization efficiency under saline irrigation (Ayman *et al*., 2020; Salem *et al*., 2017a). Productivity of irrigation water rose from 1.14 to 1.35 kg m^{-3} in the first season and from 1.16 to 1.42 kg m−3 in the second season at 200 mg l−1, reflecting improved water-use under stress that agrees with nano-silica mediated gains in photosynthesis and water status reported for wheat in saline soils (Ayman *et al*., 2020; Salem *et al*., 2017a). Mechanistically, these responses may be due to enhanced photosynthesis, antioxidant capacity, osmotic adjustment, and K/Na homeostasis induced by foliar nano-silica mechanisms increasingly evidenced in wheat and supported here by the consistent field gains across yield components, nutrient uptake, protein, NUE, N recovery, and PIW (Osman *et al*., 2017; Ayman *et al*., 2020).

The interaction between KH and Si-NPs worked together to improve ionic balance and root vigor through KH-mediated chelation and cation exchange capacity, as well as Si-driven osmotic adjustment and antioxidant protection. This increased spikes m^{-2} under salinity conditions (Salem *et al*., 2017a; Osman *et al*., 2017; El-Etr and Hassan, 2017; Shabana *et al*., 2023). The grain set increased because the combined KH and Si-NPs improved K nutrition, chlorophyll stability, and the detoxification of reactive oxygen species (ROS), which led to more grains per $spike^{-1}$ (Salem *et al*., 2017a, 2017b; Osman *et al*., 2017; Ali *et al*., 2023). The thousand-kernel weight increased due to KH enhancing assimilate supply and root absorption, while Si-NPs preserved membrane integrity and facilitated sugar translocation under saline osmotic stress, hence promoting grain filling (Benito *et al*., 2023; Salem *et al*., 2017a; Ayman *et al*., 2020; Rashed *et al*., 2022). With 10 kg KH fed^{-1} + 200 mg Si-NPs l^{-1} consistently optimizing yield components and final yield through additive improvements in nutrient acquisition, water status, and stress physiology, grain yield responded most favorably to the combined inputs. However, the KS interaction had no significant effect on straw yield, suggesting sink-driven gains rather than vegetative mass (Salem *et al*., 2017a; Osman *et al*., 2017; Shabana *et al*., 2023). The KS interaction significantly increased N, P, and K uptake in grain and straw by enhancing root architecture and rhizosphere chemistry (KH) and sustaining transporter activity and ion selectivity (Si), explaining the large upticks in NPK accumulation under the top rates (Salem *et al*., 2017b; El-Etr and Hassan, 2017; Abo-Samrh *et al*., 2023; Ali *et al*., 2023). Protein content rose under KH × Si-NPs because improved N uptake and assimilation (via KH-stimulated metabolism and Si-supported photosynthesis) increased grain N deposition, with the highest protein at the combined maximum rates (Salem *et al*., 2017b; Ayman *et al*., 2020; Ali *et al*., 2023). The KS interaction enhanced NUE and N recovery % by increasing nitrogen uptake and conversion efficiency into grain, aligning with nitrogen efficiency theory for cereals and the documented dose-dependent response to KH and Si-NPs (Craswell and Godwin, 1984; Du *et al*., 2021; Benchelali *et al*., 2022; Salem *et al*., 2017a). PIW increased markedly with KH × Si-NPs due to better soil moisture retention and structure (KH) plus improved leaf water relations and stomatal regulation (Si), with the 10 kg KH + 200 mg Si-NPs combination yielding the highest PIW under drip irrigation (Awwad *et al*., 2015; Michael, 1987; Salem *et al*., 2017a).

The interaction among cultivar, KH and Si-NPs significantly affected grain yield per feddan and PIW. Misr 1 exhibited the most pronounced synergistic response at 10 kg KH fed^{-1} plus 200 mg Si-NPs l^{-1}, achieving yields of 2.932–3.265 t fed^{-1} and a PIW of up to 1.58 kg grain m^{-3}. This genotype-specific advantage corresponds with independent evidence of Misr 1 and Shandaweel 1's salinity tolerance and consistent performance under salt stress (Elhag 2023; Ebaid *et al*. 2019; El Hendawy and Hassan 2017). Conversely, CKS did not significantly affect yield components (spikes m^{-2}, grains $spike^{-1}$, 1000-grain weight) or straw yield, indicating that improvements in these traits arose primarily from a consistent KH×Si-NPs two-way synergy across cultivars via enhanced root growth, soil structure and water retention, nutrient availability, photosynthesis, and antioxidant defense (Salem *et al*. 2017a & 2017b; El-Etr and Hassan 2017; Osman *et al*. 2017; Shabana *et al*. 2023). Similarly, for N, P, and K uptake in grain and straw and for grain protein content, the CKS interaction was non-significant. At the same time, KH×Si-NPs were significant, implying cultivar-independent gains in nutrient acquisition and N assimilation driven by KH-mediated rhizosphere/root improvements and Si-NPs-mediated stress mitigation and nutrient transport (Salem *et al*. 2017a, 2017b; Benito *et al*. 2023; Abd-Elzaher *et al*. 2022; Ayman *et al*. 2020; Rashed *et al*. 2022). Similarly, nitrogen use efficiency and N recovery were markedly improved by KH×Si-NPs. Still, they showed no significant CKS effect, indicating that fertilizer-use efficiency gains are broadly consistent across genotypes and consistent with reports that nano-silica and humic substances enhance N economy and can reduce N fertilizer requirements under salinity (Ali *et al*. 2023; Salem *et al*. 2017a; Benchelali *et al*. 2022). Generally, the cultivar-dependent synergy is most clear in grain yield and PIW. Misr 1 with 10 kg KH fed^{-1} plus 200 mg Si-NPs l^{-1} produced the best results. Improvements in yield components, nutrient uptake, protein, NUE, and N recovery mostly show strong KH×Si-NPs effects that are similar across cultivars in saline conditions (Awwad *et al*. 2015; Salem *et al*. 2017a, 2017b; Osman *et al*. 2017).

5. Conclusions

The study advocates for the simultaneous application of 10 kg of KH per feddan and a foliar spray of 200 mg l^{-1} Si-NPs, particularly with the Misr1 wheat cultivar, to enhance wheat growth, yield, nutrient absorption, protein content, NUE, and PIW in saline soil conditions utilizing drip irrigation. This comprehensive strategy efficiently alleviates salt stress and improves overall wheat yield and quality.

Declarations

Ethics approval and consent to participate

Author Contributions: All authors helped prepare the MS and agree to publish it.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: There is no conflict of interest among the authors.

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6. References

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