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Research Article

Assessing agro-biochemical characteristics of *Triticum aestivum* L. by nano fertilizer applications under varied salinity levels of irrigation water

Raghad Sabbar Abbas[1], Ayyad W. Al-Shahwany[2], Leila Zarandi-Miandoab[1*] and Nader Chaparzadeh[1]

[1] Department of Biology, Azarbaijan Shahid Madani University (ASMU), Azarbaijan, Iran
[2] Department of Biology, College of Science, University of Baghdad, Baghdad, Iraq

Abstract

This study focuses on improving the growth and tolerance of wheat (*Triticum aestivum* L.) when irrigated with saline well water, a common challenge in areas with limited freshwater resources. The research evaluates the effectiveness of nano fertilizers, specifically IQ Combi and nano silicon, in enhancing wheat performance under saline conditions. Field experiments were conducted during the autumn seasons of 2022 and 2023 using a randomized complete block design with three replicates. Irrigation was carried out every 18 days using three levels of salinity (0, 50, and 75 mM NaCl). Nano fertilizers were applied as foliar sprays three times, beginning after the third leaf appeared and repeated every 15 days. The results showed that increasing salinity levels negatively affected key agronomic traits such as plant height, flag leaf size, number of tillers, and total biomass. Furthermore, there was a noticeable reduction in biochemical compounds, including carbohydrates, proteins, and both reducing and non-reducing sugars. However, the application of nano fertilizers improved all measured traits, with higher concentrations yielding better results. In particular, IQ Combi and nano silicon significantly increased the salt tolerance of the wheat variety 'IPA 99', especially under the highest salinity level (75 mM), by supporting growth and metabolic activity.

Keywords: Agro-biochemical, Nano Fertilizer, *Triticum aestivum*, Well Water

Introduction

Salinity in irrigation water and soils remains one of the most significant abiotic stresses impacting global agriculture. Over the past two decades, this challenge has intensified, particularly in arid and semi-arid regions like the Mediterranean, where increased irrigation demands have exacerbated soil salinization (Acosta-Motos *et al*., 2017). Water quality is crucial for sustainable agriculture, as the use of saline water for irrigation leads to soil degradation, negatively affecting crop productivity and economic viability under conventional farming practices. Groundwater, a vital resource in arid regions, contains varying concentrations of salts that can inhibit crop growth and alter soil properties. The presence of particular ions, such as Na^+, CO_3^{2-}, and HCO_3^-, can exacerbate soil alkalinity and sodicity, leading to conditions that hinder plant growth (Tao *et al*., 2021). Wheat (*Triticum aestivum* L.), a staple crop in these regions, is particularly susceptible to saline stress, which impairs its physiological and biochemical processes, ultimately reducing yield potential.

To address these challenges, recent advancements in sustainable agriculture have focused on the use of nano-fertilizers to enhance nutrient efficiency and mitigate abiotic stress, particularly salinity. Nano-fertilizers, with their increased surface area and solubility, promote targeted nutrient release, improving nutrient uptake and plant resilience under stress conditions (Subramanian *et al*., 2015; Ghafari *et al*., 2018). Among these, IQ Combi, a nano-formulated fertilizer enriched with micronutrients (Fe, Zn, Mn, Cu), serves as both a fertilizer and a biostimulant. Nanofertilizers enhance physiological processes, enzymatic activities, and

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*Corresponding Author : zarandi @azaruniv.ac.ir

photosynthetic efficiency, promoting better plant growth and stress tolerance. They improve nutrient uptake, stimulate root development, and increase antioxidant enzyme activity, contributing to enhanced plant resilience under abiotic stress (Zheng *et al*., 2023). Additionally, nano-silicon plays a critical role in strengthening cell walls, improving osmotic regulation, and activating antioxidant enzymes such as SOD and CAT, which help mitigate oxidative stress from saline environments (Gong *et al*., 2005; Zhu *et al*., 2019). Nano-silicon has also been shown to improve root development, modulate hormonal balance (auxins and gibberellins), and enhance overall plant resilience (Tarafdar *et al*., 2014; Rastogi *et al*., 2019; Mahajan *et al*., 2011). This study aims to assess the growth performance of wheat under saline well-water conditions, focusing on the effects of nano-silicon and IQ Combi on key agro-biochemical parameters. The goal is to identify effective strategies for improving wheat productivity in saline environments.

Materials and methods

A field experiment was conducted to investigate the agronomic traits of wheat (*Triticum aestivum* L. cv. IPA 99) under varying levels of saline well water in combination with two types of nano-fertilizers. The study was carried out during the autumn growing seasons of 2022 and 2023 in one of the agricultural fields located in Baqubah District, Diyala Governorate, Iraq.

Experimental design: The experiment was conducted using a Randomized Complete Block Design (RCBD) with three replications to minimize the effect of environmental variation among experimental units and to increase the accuracy of the statistical analysis. A split-split plot arrangement was used within each replication due to the presence of three experimental factors with multiple levels. The main plots were assigned to different levels of irrigation water salinity (M), as this factor is difficult to change frequently and requires separate irrigation systems. The sub-plots received different nano-silicon (S) treatments at varying concentrations, while the sub-sub-plots were treated with different concentrations of the IQ Combi bio-stimulant (Q). Although nano-silicon and IQ Combi were placed at different levels of the experimental layout (sub- and sub-sub-plot, respectively), they were treated as equally important factors in terms of their biological significance and expected effects on plant response under salinity stress. This arrangement was based on practical considerations related to field application and not on the relative scientific importance of the treatments. All treatments were randomly assigned within their respective plot levels to ensure proper statistical distribution and to allow for the analysis of individual effects as well as interactions among the three studied factors: salinity, nano-silicon, and IQ Combi. Nano-silicon was procured from Merck Life Science UK Limited (United Kingdom), and IQ Combi was sourced from AGRI SCIENCES (USA). The physicochemical characteristics of both nano-fertilizers were examined using Atomic Force Microscopy (AFM) and Transmission Electron Microscopy (TEM). Each experimental unit consisted of a pot filled with approximately 20 kg of soil, sown with 10 seeds at a depth of 4 cm. Irrigation with tap water was applied immediately after planting to ensure uniform germination. Eighteen days post-planting, irrigation treatments with saline well water were initiated. Two salinity levels were used: 50 mM and 75 mM NaCl, in addition to a control treatment using tap water. Foliar applications included distilled water (control), two concentrations of IQ Combi (1 g/L (IQ1) and 2 g/L(IQ2)), and two concentrations of nano-silicon (1.6 mmol/L (S1) and 3.2 mmol/L (S2)). These foliar treatments were applied three times during the growing season, starting after the emergence of the third leaf and subsequently every 15 days. The application of nano-fertilizers was performed in the early morning at the same time for both types, and on dry leaves.

Agronomic traits: Plant height was measured using a tape or ruler from the base of the plant (at soil level) to the topmost point of the plant. The plant was required to be upright and not leaning (Ali, 2017). Measurement of the flag leaf (length and width) was conducted using a ruler or caliper to ascertain the length, which was defined as the distance from the point of attachment of the flag leaf to the stem to the apex of the leaf, and the width, which was determined by evaluating the broadest section of the leaf (Sikder, 2009). The method for counting tiller numbers involved visual enumeration, which quantified the number of tillers arising from the base of the primary plant (Fischer, 1985). Chlorophyll content was measured using a SPAD chlorophyll meter. The chlorophyll meter clip was placed on the flag leaf, and readings were taken (Porra, 2002). To obtain fresh biomass, the wheat crops were harvested and weighed. This was done by collecting the entire plant or a representative sample, removing the soil, and weighing it immediately to get the fresh weight (Gomes *et al*., 2007). Dry and fresh plant material was placed in an oven at 70°C until constant weight was achieved, then weighed, and dry biomass was obtained (Blum, 2011).

Biochemical traits: Carbohydrates were extracted from the plant sample using an appropriate solvent: hot water. Then carbohydrate extract was mixed with anthrone reagent and heated in a water bath. Carbohydrate contents were calculated with the absorbance at 620 nm using a spectrophotometer (Miller, 1959). Protein was determined using the Kjeldahl method (Goyal *et al*., 2022). The Kjeldahl method was started by digesting the sample with sulfuric acid and a catalyst, neutralizing with sodium hydroxide, and distilling the ammonia by adding titrate to the distillate with a standard acid solution. After that, calculate protein content based on nitrogen content. The Dubois *et al*. (1956) method was used to determine the total sugars. Reducing sugar content is calculated

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according to Miller (1959). The dinitrosalicylic acid (DNS) method was started by extracting sugars from the sample. After that, mix with DNS reagent and heat in a boiling water bath, and measure absorbance at 540 nm. After determining total and reducing sugars, calculate non-reducing sugars. The method was according to Nelson (1944). Subtract the amount of reducing sugars from total sugars to find non-reducing sugars.

Statistical analysis: Statistical analysis was conducted using the GenStat software. The data were subjected to analysis of variance (ANOVA) appropriate for a split-split plot design within a Randomized Complete Block Design (RCBD). This approach was used to evaluate the main effects and interactions among the three experimental factors: irrigation water salinity, nano-silicon, and IQ Combi. Differences among treatment means were assessed using the Least Significant Difference (LSD) test at the 0.05 probability level (corresponding to 95% confidence), which served as the criterion for determining statistical significance between means.

Results and discussion

Soil properties are illustrated in Table 1. Irrigation water characters are shown in Table 2. he weather of the 2022 and 2023 growth seasons was recorded as shown in Table 3.

Nano-silicon: occupies a pivotal role in the enhancement of plant physiology, particularly in response to stress conditions. It facilitates plant growth and productivity by fortifying cellular membranes, augmenting photosynthetic efficiency, and modulating water absorption. Furthermore, nano-silicon establishes protective barriers that diminish pathogen ingress and alleviate abiotic stresses such as saline conditions and drought. Empirical research has corroborated its function in the activation of antioxidant defense mechanisms, which are instrumental in the scavenging of reactive oxygen species and the amplification of plant resilience and overall fitness. Moreover, nano-silicon enhances the uptake and utilization of nutrients, thereby further contributing to the overall vigor of plants (Mokdad *et al*., 2015).

The topographical and three-dimensional images of nano-silicon, obtained via atomic force microscopy (AFM), revealed that the synthesized particles exhibited a predominantly spherical morphology (Figures 1 and 2). Additionally, nanoparticle agglomeration was observed. Field emission scanning electron microscopy (FE-SEM) images (Figure 3) confirmed the nanoscale structure of the material, with particle diameters ranging from 16.99 to 38.33 nm and an average size of approximately 25.12 nm. The inclusion of a 500 nm scale bar facilitated accurate dimensional interpretation. Furthermore, visible particle agglomeration was noted, which is commonly associated with high surface energy in nanoparticulate systems. These findings aligned with the histogram-based particle size distribution analysis and confirmed the classification of the material as a nanomaterial. This characterization approach is consistent with recent findings that support the combined use of AFM and SEM for accurate nanoparticle analysis (Wollschlager *et al.*, 2015).

Both the topography and three-dimensional images, which are shown by atomic force microscope (AFM) IQ Combi images, revealed the globally spherical shape of the prepared particles (Figures 4 and 5). Also, nanoparticle agglomeration is observed.

Field Emission Scanning Electron Microscopy (FE-SEM) was employed to investigate the morphology and particle size of the synthesized nano-fertilizers. Two representative images were captured at different magnifications (100,000× and 25,000×) to ensure accurate visualization and assessment of nanoparticle structure. In the figure 6 image at 25,000× magnification, the particle sizes ranged between 11.66 nm and 63.71 nm, with a slightly higher average size of about 35.22 nm. Despite the lower magnification, the particle boundaries remained distinguishable, and agglomeration was again observed, reinforcing the findings from the previous image.

In this study, the average diameter of the Nano-silicon fertilizer nanoparticles was 35 nm (Figure 3), while the IQ Combi fertilizer nanoparticles were 58nm (Figure 6). Optical properties of nanoparticles are sensitive to several factors such as size, shape, concentration, agglomeration state, and refractive index near the nanoparticle surface, which makes topography and three-dimensional images a valuable tool for identifying, characterizing, and studying these materials (Rizwan *et al*., 2015).

Nano-Silicon and IQ Combi on agronomic traits of wheat: The synergistic influence of nano-silicon and IQ Combi on the agronomic characteristics of the wheat cultivar IPA 99 (*T. aestivum* L.) under well-saline conditions is presented in Table 4. Irrigation with saline water exerts significant effects on various agronomic traits, particularly at a concentration of 75 mM. The chlorophyll content demonstrated a noteworthy difference, with the lowest measurement recorded at 50.53 SPAD units and the highest at 60.60 SPAD units. Furthermore, the flag leaf area varied from a minimum of 22.045 cm² to a maximum of 32.01 cm². The plant height exhibited a minimum of 65.19 cm and a maximum of 99.33 cm. The number of tillers per plant also exhibited significant variation attributable to salinity, with a mean value of 6.315 and a maximum of 10. Nevertheless, the fresh biomass revealed a significant difference, with the lowest mean being 6.075 g and the highest at 8.96 g. Lastly, the dry biomass recorded a minimum mean of 2.045 g and a maximum of 5.51 g.

Well water typically results in a decrease in chlorophyll content due to its adverse effects on chlorophyll biosynthesis and the stability of chloroplasts. Elevated salinity levels lead to a significant reduction in chlorophyll a and b, which are essential for the process of photosynthesis (Atta *et al*.,

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Table 1. Some chemical and physical properties of the experimental soil before planting

Chemical properties							Physical properties			
(pH)	ECe (dsm^{-1})	N	P	K	Na	Cl	Sand	Silt	Clay	Soil texture
		($mg\ kg^{-1}$)			($ml.\ L^{-1}$)		($g.kg^{-1}$)			
8.07	13.6	13.45	4.02	204.55	1.83	1.88	39.5	43.7	1.6	Loam

Table 2. Some chemical analysis of the water used in the experiment

Parameter	Unit	Tap Water	Saline Well Water (50 mM)	Saline Well Water (75 mM)
TDS	$mg \cdot L^{-1}$	510	633	922
pH	—	7.7	7.2	7.3
EC	$dS \cdot m^{-1}$	1.33	4.2	6.7
Na	$mmol \cdot L^{-1}$	8.68	13.02	15.19
Ca	$mmol \cdot L^{-1}$	31.12	33.11	35.12
Cl	$mmol \cdot L^{-1}$	131.05	176.4	191.82
K	$mmol \cdot L^{-1}$	8.21	10.9	22.1
Mg	$mmol \cdot L^{-1}$	9.12	27.31	35.12
S	$mmol \cdot L^{-1}$	0.34	0.53	0.82
NO_3	$mmol \cdot L^{-1}$	1.01	23	25

Table 3. The Average maximum and minimum temperature and rainfall in both growth seasons

Growth seasons	Average maximum temperature °C	Average Minimum temperature °C	The mean of rainfall mm
2022	22.63	10.58	185.8
2023	23.29	10.04	280.8

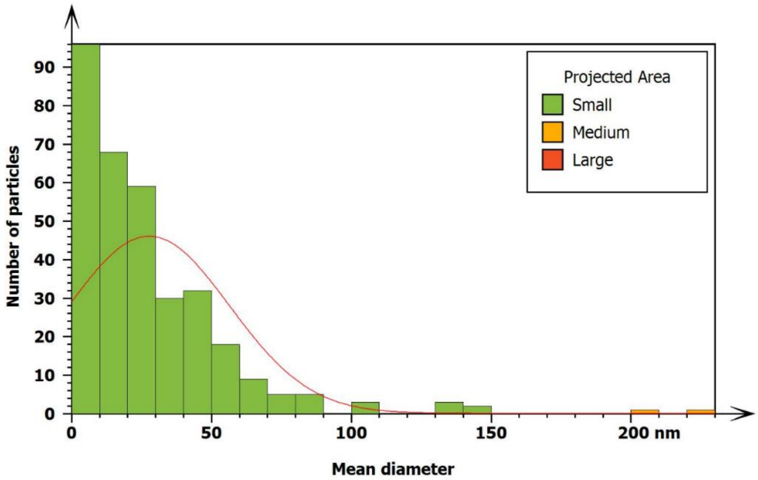

Figure 1. Granularity accumulation distribution chart obtained from SEM micrograph for Nano-silicon fertilizer

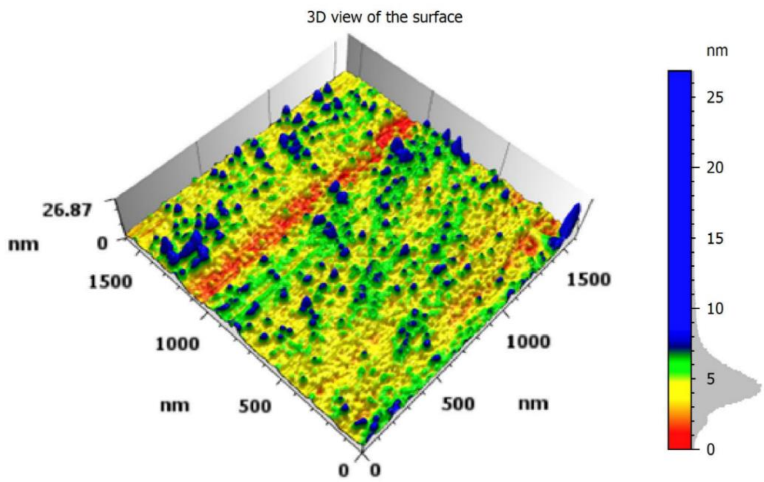

Figure 2. Topography and three-dimensional images that show the globally spherical shape of Nano-silicon fertilizer

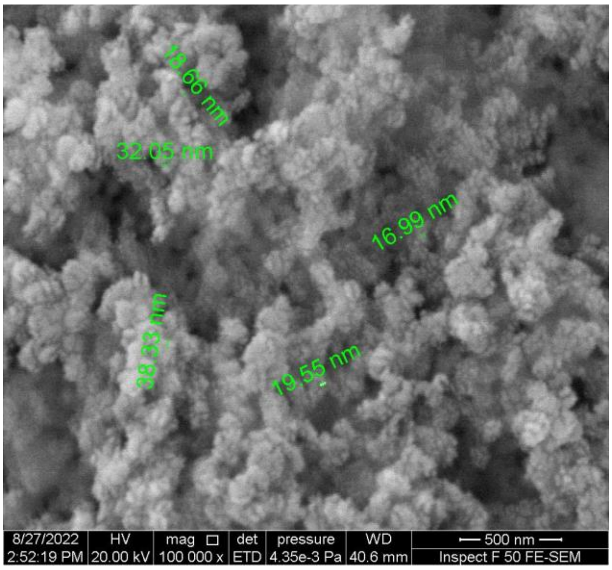

Figure 3. FE-SEM image showing the morphology and size distribution of synthesized nano-silicon fertilizer.

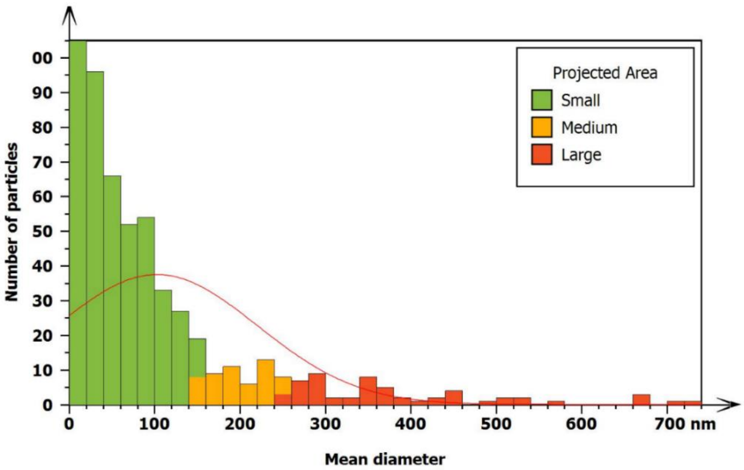

Figure 4. Granularity accumulation distribution chart obtained from SEM micrograph for IQ Combi fertilizer

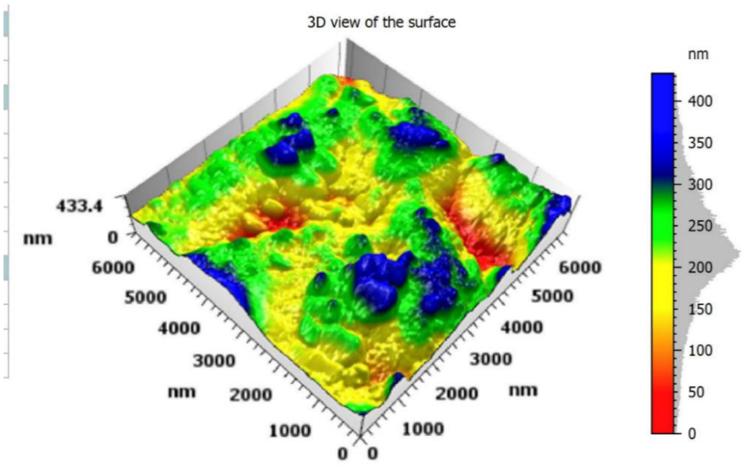

Figure 5. Topography and three-dimensional images showing IQ Combi fertilizer's globally spherical shape

2023). This stress negatively impacts the efficiency of photosystem II, thereby diminishing the overall photosynthetic capacity of the plant. Conversely, the application of nano-silicon and IQ Combi in saline conditions has been shown to enhance chlorophyll content, highlighting the potential advantages of this treatment. The analysis of the flag leaf indicates that well water reduces its area, consequently limiting the

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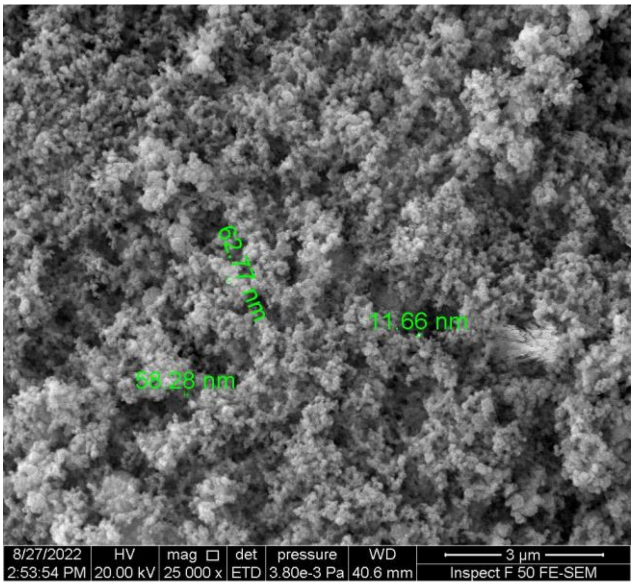

Figure 6. FE-SEM image of IQ combi fertilizer particles showing surface morphology and nanoscale dimensions

Table 4. Synergistic effects of nano-silicon and IQ combi on some agronomy traits of wheat under saline irrigation in the 2022 and 2023 growth seasons

Treatments	The means of the treatments					
	Chlorophyll (SPAD)	Flag Leaf (cm^2)	Plant Height (cm)	Tiller Numbers	Fresh Biomass (g)	Dry Biomass (g)
Control value 2022	55.66	29.36	77.33	8.33	8.33	3.67
Control value 2023	60.90	29.00	93.33	8.00	9.00	3.60
S1	57.645	29.27	73.775	7.275	7.66	3.31
S2	55.865	28.77	95.645	8.475	8.46	3.755
Q1	59.815	27.065	72.92	7.33	7.625	3.26
Q2	55.22	28.845	98.145	8.5	8.44	3.75
M1	50.53	22.045	65.195	6.315	6.075	2.045
M2	52.15	23.235	65.92	6.18	6.495	2.485
SxM1	64.9	30.455	73.61	7.385	7.66	3.22
SxM2	60.535	30.23	95.27	7.83	8.495	3.99
QxM1	60.495	29.445	73.885	8.05	7.235	3.28
QxM2	56.31	29.11	96.11	8.16	8.515	3.715
SxQxM1	59.815	32.01	84.495	9.00	8.66	4.5
SxQxM2	60.605	31.815	99.33	10.0	8.96	5.51
L.S.D ≤ 0.05	S,Q,m =0.779 SM=3.66 QM=3.30 SQM=5.294	S,Q,m =0.22 SM=4.11 QM=4.85 SQM=5.80	S,Q,m =1.36 SM=3.81 QM=3.36 SQM=5.61	S,Q,m =0.28 SM=0.87 QM=0.62 SQM=0.86	S,Q,m =0.26 SM=0.80 QM=0.75 SQM=1.06	S,Q,m =0.18 SM=0.81 QM=0.84 SQM=0.88

Q; IQ Combi (Q1=1 g/L and Q2=2 g/L), and S; Nano-silicon (S1= 1.6 mmol/L, S2= 3.2 mmol/L), M; Saline, 1; 2022 and 2; 2023 growth seasons.

photosynthetic surface available for leaf filling. This reduction is primarily due to osmotic stress and ionic toxicity resulting from high salt concentrations, which hinder cell expansion and division (Seymen *et al*., 2023; Ali *et al*., 2004). However, the introduction of nano-silicon and IQ Combi in saline environments significantly increases the flag leaf area, alleviating the adverse effects of salinity stress. Additionally, well water contributes to shorter plant stature due to osmotic stress and ionic toxicity, which impair water uptake and disrupt cellular functions and growth hormones, particularly under saline conditions. In contrast, the use of nano-silicon and IQ Combi in saline environments leads to significantly taller plants, demonstrating its efficacy in counteracting these detrimental effects. In the absence of treatment, the combined impact of osmotic stress and ionic toxicity stunts overall plant growth, resulting in reduced height compared to plants cultivated in non-saline conditions (Ali *et al*., 2004; Belkhodja *et al*., 1999). Furthermore, the production of tillers is significantly influenced by salinity. High salinity levels diminish the number of tillers per plant by disrupting the hormonal balance and nutrient uptake essential for tiller initiation and development. Consequently, a reduced number of tillers results in lower potential leaf production per plant. The notable

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impact of nano-silicon and IQ Combi treatment has been clearly demonstrated.

The notable impact of nano-silicon and IQ Combi treatments was evidenced by a substantial increase in the number of tillers, with significant variations observed, highlighting the potential advantages of these treatments (Seymen *et al*., 2023; Ali *et al*., 2004). These results emphasize the necessity of developing and utilizing salt-tolerant wheat varieties, alongside management strategies that alleviate the adverse effects of salinity, to promote sustainable wheat production in saline irrigation environments. This approach resulted in enhanced fresh and dry biomass, particularly with the combinations of nano-silicon + salinity, IQ Combi + salinity, and nano-silicon + IQ Combi + salinity treatments.

The data illustrated in Figure 7 reveal the substantial effects on various agronomic characteristics of wheat subjected to saline irrigation. The use of well water led to a reduction in chlorophyll content by 9.2% and 14.36%; however, the application of nano fertilizers elevated the chlorophyll levels to between 9.2% and 6.5% in wheat leaves during the 2022 and 2023 growth seasons. Additionally, salinity caused a decrease in plant height ranging from 15.69% to 29.34%, while treatments involving nano-silicon and IQ Combi enhanced plant height by 9.14% to 6.43% for the same growth periods. Salinity also adversely affected the flag leaf area, resulting in a reduction from 24.94% to 19.89%, yet the combined effects of nano-silicon and IQ Combi led to an increase in flag leaf area from 9.35% to 9.65% during the 2022 and 2023 growth seasons. Significant reductions were noted in the number of tillers, with a decrease of 27.13% to 22.75%, although the impact of nano fertilizers was minimal, ranging from 8.3% to 25%. The fresh biomass percentage experienced a decline of 27.13% to 27.19% under salinity stress, while the synergistic effect of nano-silicon and IQ Combi resulted in an increase of 3.6% to 11.1%. Finally, the use of well water led to a decrease in dry biomass by 33.2% to 25.5%, whereas the application of nano fertilizers resulted in an increase in dry biomass by 22.6% to 41.6% for the 2022 and 2023 growth seasons.

The study refers to highlighting the impact of well water on various agronomic traits of wheat and the mitigating effects of applying nano fertilizers, specifically nano-silicon and IQ Combi, over the 2022 and 2023 growth seasons. Well water typically reduces chlorophyll content, impairing photosynthesis and plant growth (Hussain, 2018), while Nano-silicon has been shown to enhance chlorophyll content under stress conditions by improving nutrient uptake and reducing oxidative damage (Rastogi *et al*., 2019). Also, well water inhibits plant growth by causing osmotic and ionic stress, leading to stunted growth (Munns and Tester, 2008). Nano-silicon can mitigate these effects by enhancing water uptake and cell elongation, thereby promoting growth (Liang *et al*., 2007). The flag leaf area is crucial for photosynthesis and grain filling. Salinity reduces leaf area due to osmotic stress and ion toxicity (Khan, 2016). Nano-silicon helps maintain leaf area by improving photosynthetic efficiency and reducing stress-induced damage (Gong, 2003). However, tiller number is a critical yield component, and well water can significantly reduce tillering (Ashraf, 2004). While nano-silicon helps, its effect on tillering might be less pronounced compared to other traits (Siddiqui, 2014). Besides, the well water reduces biomass by affecting water uptake and nutrient assimilation (Parida and Das, 2005). Nano-silicon can enhance biomass by improving water use efficiency and stress tolerance (Gao *et al*., 2004). Dry biomass is a direct indicator of crop yield. Well water reduces it significantly (Zhu, 2001). Nano-silicon increases dry biomass by improving overall plant health and resilience to stress (Ma *et al*., 2004).

Nano-silicon and IQ Combi on biochemical traits of wheat: Table 5 shows the synergistic effects of nano-silicon and IQ Combi on leaf biochemical composition under saline irrigation in the 2022 and 2023 growth seasons. Irrigation of wheat plants with saline water significantly decreased carbohydrates in the plant leaves. In addition, the lowest mean was 5, while the highest was 12.7. Meanwhile, saline water significantly decreased protein content. The lowest percentage for the protein was 12.675% for M, while the highest rate was 17.815% for nano-silicon + IQ Combi + salinity in the first growth season, respectively. On the other hand, irrigation of wheat plants with 75 mM saline water significantly decreased total sugar. The lowest mean was (4.26 mg/g FW. However, treating wheat plants either with Nano-Silicon or IQ Combi resulted in obvious significant increases in total sugar contents, especially in plants treated with their combination, which recorded 9.6 mg/g FW. Foliar application of the wheat leaf nano fertilizer, especially at nano-silicon + IQ Combi + salinity, increased the reducing and non-reducing sugar to 0.229 and 2.15 compared with the lowest treatment of 0.54 and 4.60, respectively.

Well water significantly impacts the biochemical composition of wheat leaves, affecting carbohydrates, proteins, and various sugar contents. The well water generally reduces the total carbohydrate content in wheat leaves. This reduction is mainly due to the adverse effects of salt on photosynthesis, which diminishes the overall carbohydrate synthesis and storage in the plant tissues (Azizi *et al*., 2024; Sadak and Talaat, 2021). Also, the protein content in wheat leaves tends to decrease under saline conditions. High salinity levels can impair nitrogen uptake and assimilation, leading to lower protein synthesis. However, some studies indicate that specific genotypes of wheat may maintain or even increase protein content as a stress response, potentially as a protective mechanism to maintain osmotic balance (Sihmar *et al*., 2024; Hussein *et al*., 2022). The total sugar content, which includes both reducing and non-reducing sugars,

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Table 5. Synergistic effects of nano-silicon and IQ Combi on biochemical composition of wheat leaves under saline irrigation during the 2022 and 2023 growth seasons

Treatments	The means of the treatments				
	Carbohydrate (mg/g)	Protein (%)	Total sugars (mg/g)	Reducing sugars (mg/g)	Non reducing sugars (mg/g)
Control value 2022	6.12	14.26	6.85	0.473	3.94
Control value 2023	7.88	18.31	7.06	0.480	4.31
S1	6.16	16.85	6.45	0.3625	2.935
S2	7.27	17.485	6.32	0.329	3.24
Q1	6.32	17.815	6.03	0.369	3.055
Q2	7.27	16.88	6.32	0.3125	3.185
M1	5.00	12.675	4.26	0.254	2.15
M2	6.03	14.88	4.395	0.229	2.26
SxM1	6.925	17.32	6.58	0.3555	3.105
SxM2	7.985	16.38	6.765	0.321	3.15
QxM1	6.9	17.255	5.94	0.3825	3.215
QxM2	7.59	17.3	5.925	0.342	3.325
SxQxM1	10.5	16.745	9.4	0.54	4.57
SxQxM2	12.7	17.14	9.6	0.514	4.60

Q; IQ Combi (Q1=1 g/L and Q2=2 g/L), and S; Nano-silicon (S1= 1.6 mmol/L, S2= 3.2 mmol/L), M; Saline, 1; 2022 and 2; 2023 growth seasons., M; Saline, 1; 2022 and 2; 2023 growth seasons.

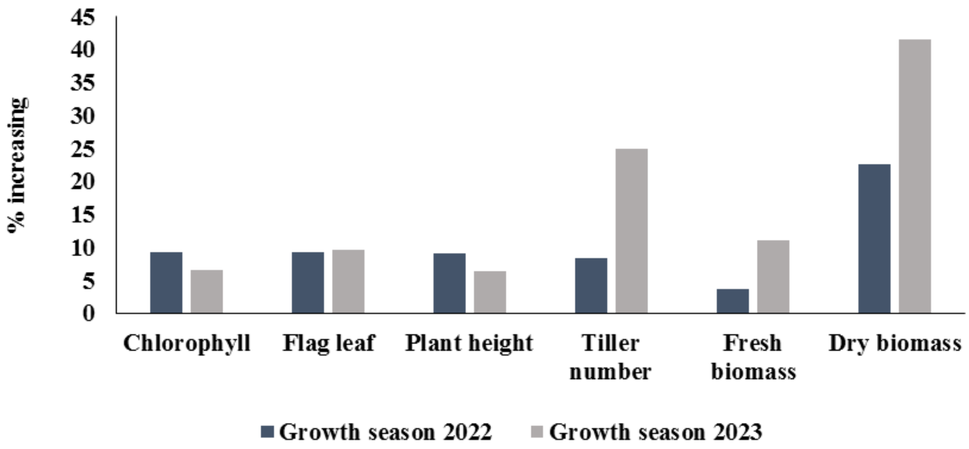

Figure 7. The increasing synergistic effects of nano-silicon and IQ Combi on some agronomic traits of wheat leaves under saline irrigation in the 2022 and 2023 growth seasons

is typically reduced under salinity stress. This reduction occurs because the plant redirects its energy from sugar production to synthesizing osmoprotectants and stress-related proteins. For this, these sugars, which include glucose and fructose, often decrease under salt stress. Reducing sugars is crucial for cellular metabolism and energy production, and their reduction can lead to diminished growth and leaf quality (Sadak and Talaat 2021). Nevertheless, sucrose, a major non-reducing sugar, can also be affected by salinity. Its levels may decrease due to impaired photosynthesis and carbohydrate metabolism, although some plants may increase sucrose content as a stress response to help in osmotic adjustment and protection against oxidative stress. Overall, well water negatively impacts wheat leaf biochemical properties, though the extent can vary depending on the wheat genotype and the severity of the stress. Enhanced salt tolerance in some genotypes involves complex physiological and biochemical adjustments that help mitigate these adverse effects (Sihmar *et al*., 2024).

The results in Figure 8 indicate the effects of well water and nano-fertilizers on the biochemical contents of wheat demonstrate scientific validity based on the current understanding of plant stress physiology and nano-fertilizer efficacy. The scientific validity of the results discussed in the study on the effects of nano-silicon and IQ Combi on the biochemical content of wheat under saline irrigation. The reduction in carbohydrate content due to well water (22.4% and 30.6%) and the subsequent increase (71-61%) with nano-fertilizers is consistent with findings that nano-fertilizers enhance nutrient uptake and stress tolerance. Nano-fertilizers, due to their controlled release properties and high nutrient use efficiency, can significantly improve plant metabolism and carbohydrate accumulation (Yadav *et al*., 2023). Also, the study's observation that salinity reduces protein

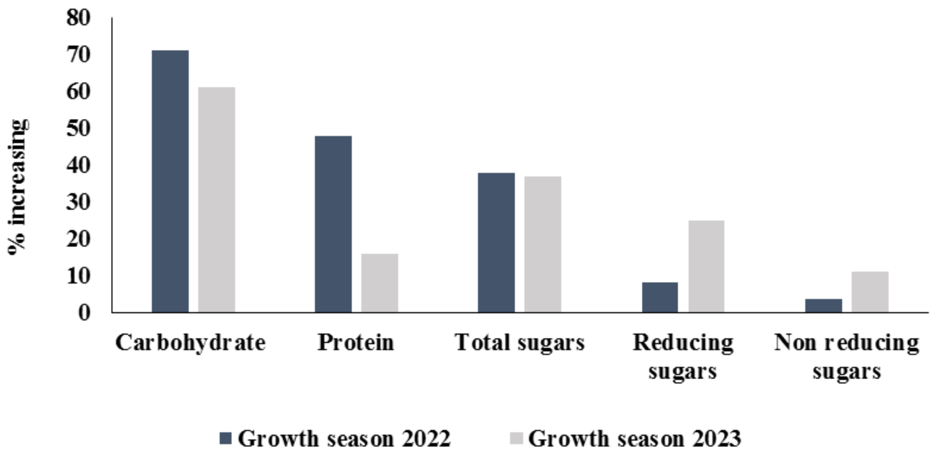

Figure 8. The increasing synergistic effects of nano-silicon and IQ Combi on some biochemical contents of wheat leaves under saline irrigation in the 2022 and 2023 growth seasons

content by 11-18% and that nano-silicon and IQ Combi treatments increase it to 48-16% aligns with research showing that nano-fertilizers can improve protein synthesis by enhancing nitrogen use efficiency. Nano-fertilizers encapsulate nutrients, reducing losses and ensuring a steady supply, which is crucial for protein synthesis under stress conditions.

Besides, the total and reducing sugars have reported a reduction in total sugar (37%) due to salinity, and the modest increase (9.35-9.65%) with nano-silicon and IQ Combi is in line with the ability of nano-fertilizers to mitigate stress impacts. These fertilizers enhance the plant's photosynthetic efficiency and sugar metabolism, even under adverse conditions. However, the negligible changes in reducing sugars (15-7%) suggest that while nano-fertilizers improve overall plant health, their effect on specific sugar types might vary based on the stress level and plant species. The reduction in non-reducing sugar percentage by 45-49% under well water and the increase by 16-7% with nano-silicon and IQ Combi treatments further corroborate the positive impact of nano-fertilizers on maintaining plant metabolic processes. Nano-fertilizers can modulate enzyme activities and metabolic pathways, thereby improving sugar partitioning and storage in plants under stress conditions (Jakhar *et al*., 2022).

Conclusion

The application of nano-silicon and IQ Combi significantly mitigates the negative effects of well water on wheat production. These strategies lead to improvements in chlorophyll levels, plant height, flag leaf area, and biomass accumulation, resulting in enhanced agricultural performance even in adverse environmental conditions. The findings support the existing literature on the benefits of nano-silicon in fostering plant growth and enhancing stress resilience. The notable changes observed in biochemical components with the use of nano-fertilizers highlight their potential to improve crop resilience and yield in saline conditions. This aligns with the broader scientific understanding that nano-fertilizers can greatly improve agricultural outcomes by facilitating better nutrient uptake and enhancing stress tolerance. These results underscore the importance of nano-fertilizers in sustainable agriculture, especially in stress-prone environments, and call for further investigation into their benefits and mechanisms of action. Nano-fertilizers are recognized for their ability to enhance nutrient use efficiency, reduce the effects of environmental stressors, and improve overall plant health and productivity.

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