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Research Article

Impact of varied nitrogen levels on agronomic performance and efficiency of nitrogen utilization by different wheat cultivars under salt-affected soil conditions

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Abstract

Optimizing nitrogen fertilization is essential for enhancing wheat productivity and promoting sustainable agriculture in salt-affected soils. This study investigated the effects of four nitrogen levels (0, 96, 192, and 288 kg N ha^{-1}) on the agronomic performance of three wheat cultivars ('Sakha-95', 'Giza-171', and 'Misr-3') in a saline soil (9.18 dS m^{-1}). Significant variations were observed in chlorophyll content, days to heading, flag leaf area, yield and its components, nutrient content (N, P, K), protein content, nitrogen uptake, nitrogen utilization efficiency (NUtE), and nitrogen use efficiency (NUE) across nitrogen levels and cultivars. Most traits improved with increasing nitrogen levels up to 288 kg N ha^{-1}, except for canopy temperature depression (CTD) and NUE, which declined. 'Sakha-95' showed the best performance in several parameters. Additionally, 'Sakha-95' exhibited the highest efficiencies in agronomic efficiency (AE), physiological efficiency (PE), apparent recovery efficiency (ARE), NUtE, and NUE. 'Misr-3' excelled in agro-physiological efficiency (APE). The interaction between nitrogen levels and cultivars was crucial in determining optimal growth conditions, with 'Sakha-95' and 'Giza-171' performing best at 288 kg N ha^{-1}. Interaction effects showed that 'Sakha-95' had the earliest heading at 0 and 96 kg N ha^{-1}, while 'Misr-3' showed the highest grain phosphorus content and PE at 288 kg N ha^{-1}. Principal component analysis (PCA) and factor analysis indicated key variables influencing agronomic performance under saline conditions. By identifying cultivar-specific responses to nitrogen application, this study offers practical recommendations for improving wheat productivity and nitrogen efficiency under saline conditions, supporting sustainable agricultural practices in such challenging environments.

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Keywords: genotypic performance; nutrient efficiency; nitrogen optimization; nitrogen use efficiency; stress tolerance; sustainable agriculture; wheat management

Introduction

Wheat (*Triticum aestivum* L.) is the most important cereal crop globally, followed by maize and rice (Ji *et al.,* 2024). Approximately 808.4 million tons of wheat are produced each year from 219.2 million hectares worldwide (FAOSTAT 2024). In Egypt, wheat is grown on 1.43 million hectares, producing 9.7 million tons annually (FAOSTAT, 2024). Despite this, wheat production in Egypt falls short of national consumption needs, leading to the importation of over 45% of the country wheat requirements. Therefore, wheat production should be increased to close the gap between consumption and production.

Due to the critical function of nitrogen in plant growth, development, and yield, nitrogen is critical for wheat production. Adequate nitrogen availability enhances tillering, promotes vigorous growth, and increases size and number of grains, directly influencing overall yield (Mansour *et al.,* 2017). Moreover, nitrogen is critical for achieving high grain protein content, which is important for wheat quality, especially in bread-making cultivars. Without sufficient nitrogen, wheat plants exhibit poor growth, reduced yield, and lower grain quality, making it a crucial element for successful wheat farming (Kamara *et al.,* 2024).

In the context of climate change, efficient nitrogen use is crucial not only for improving crop productivity but also for reducing the environmental impact of agriculture (Govindasamy *et al.,* 2023; Srivastav *et al.,* 2024). Nitrogen fertilization, while essential for boosting crop yields, is a significant source of greenhouse gas emissions, particularly nitrous oxide, which has a much higher global warming potential than carbon dioxide (Swailam *et al.,* 2021; Basheer *et al.,* 2024). In saline environments, high salt concentrations can impede nitrogen uptake by plants, leading to reduced nitrogen use efficiency and nutrient imbalances that affect wheat growth and yield (Ashraf *et al.,* 2018). Additionally, the presence of sodium and chloride ions in the soil further increase the problem, limiting the availability of nitrogen and hindering its assimilation by plants (Fageria *et al.,* 2011a). Previous studies have elucidated the challenges of nitrogen management in salt-affected soils, where high salinity levels often restrict nitrogen uptake and utilization by plants (Hussin *et al.,* 2013; Jan *et al.,* 2013; Sun *et al.,* 2023; Nazir *et al.,* 2023; Riaz *et al.,* 2024). As a result, managing nitrogen fertilization in these soils requires an approach that considers the specific interactions between salinity, nitrogen availability, and cultivar tolerance (Heng *et al.,* 2024). Efficient nitrogen use minimizes the excess application of fertilizers, thereby reducing nitrous oxide emissions and promoting more sustainable farming practices. This study aimed to determine the optimal nitrogen level for improving both yield and protein content in salt-affected soils. The findings could offer valuable insights into the role of nitrogen fertilization in enhancing wheat productivity under saline conditions, providing critical information for breeding programs focused on developing salt-tolerant wheat cultivars. By examining how different cultivars respond to varying nitrogen levels under salt stress, the study could contribute to breeding strategies aimed at producing high-yielding, salt-tolerant wheat varieties. These cultivars could perform optimally across diverse nitrogen regimes, ultimately boosting wheat production in regions with challenging soil conditions. Accordingly, this study focused on three primary objectives: (1) to evaluate the effect of different nitrogen levels on the performance of three diverse wheat genotypes concerning grain, straw, and biological yield and their attributes in salt-affected soil; (2) to determine the differences between wheat cultivars under varying nitrogen levels across various traits in salty soil; (3) to identify the relationship between nitrogen use efficiency and its components with morpho-physiological, and yield characteristics through factor, principal component, and heatmap analyses.

Materials and Methods

Experimental site and plant material

The study was carried out at the Experimental Farm of Faculty of Agriculture, Zagazig University, Egypt (30° 34'N and 31° 31'E). The soil at the experimental site is clay-textured, with 46.2% clay, 19.3% sand, and 34.5% silt. The electrical conductivity was 9.18 dS m^{-1}, indicating salinity, which is typical of salt-affected soils. The soil pH was 7.7, classifying it as slightly alkaline. The field trial was conducted under cool to mild temperatures, with high humidity levels and variable rainfall patterns. Minimum temperatures ranged from 12.0 °C to 20.0 °C, while maximum temperatures fluctuated between 18.0 °C and 27.0 °C. Relative humidity remained consistently high, ranging from 63.0% to 71.9%. Three bread wheat cultivars (‘Sakha-95’, ‘Giza-171’, and ‘Misr-3’) were selected for this investigation. These cultivars were chosen based on their distinct differences in earliness, morpho-physiological traits, nutrient uptake, yield, and other agronomic attributes. The seeds for these cultivars were obtained from the Wheat Department at the Agricultural Research Center.

Experimental layout

A split plot in three replications was performed. The main plots were assigned for the four nitrogen levels (0. 96, 192. 288 kg N ha^{-1}), applied as ammonium nitrate (33.5% N). The three wheat cultivars (‘Sakha-95’, ‘Giza-171’, and ‘Misr-3’) were located in subplots. The seeds were sown on November 21st, in six rows 2 meters long with 15 cm spacing between rows in each plot. Nitrogen was added in two equal doses at 21 and 50 days after sowing. No organic fertilizers were used. Surface irrigation was used following the standard regional practices, with a total water application of approximately 4000 m^3 ha^{-1}. The salinity of irrigation water was 1.66 dS m^{-1}.

Soil sampling

Before nitrogen application, soil samples were collected to determine mineral concentrations. To examine physical and chemical characteristics, random samples were collected at depths of 0–30 cm from four points around the area along two opposing diagonals (Table 1). Soil samples were collected from the top 0-30 cm of the soil profile, as this depth is considered the primary rooting zone for wheat, where the majority of nutrient and water uptake occurs. This sampling depth is used to assess soil fertility and nutrient availability, ensuring that the data obtained accurately reflects the conditions directly influencing crop growth. The 0-30 cm depth is ideal for evaluating the effects of fertilization on soil properties and nutrient dynamics, as it represents the active zone where the roots interact with soil nutrients. According to Pansu and Gautheyrou (2006), the pipette method was used to analyze particle size. by Jackson (2005), soluble cations and anions were measured. The method of Watanabe and Olsen (1965) was used to calculate the amount of phosphorus that was accessible, ammonium acetate was used to extract the available potassium, and flame photometry was used to measure it (Jackson, 1973). The approach of Black *et al.* (1965) was used to calculate the amount of nitrogen that was available.

Table 1. Physical and chemical properties of the soil at the experimental site soil

Characteristic/Soil particles distribution	**Value**
Sand (%)	19.30
Clay (%)	46.20
Silt (%)	34.50
Textural class	Clay
Electrical conductivity (dS m^{-1})*	9.18
pH*	7.70
Soluble cations (mmol/L)	
Calcium (Ca^{+2})	33.33
Sodium (Na^+)	45.22
Magnesium (Mg^{+2})	4.33
Potassium (Na^+)	8.92
Soluble anions (mmol/L)	
Bicarbonate (HCO_3)	2.36
Carbonate ($CO_3^=$)	0.00
Sulphate ($SO_4^=$)	19.10
Chlorine (CL)	70.34
Available nutrient (mg/kg soil)	
Phosphorus (P)	11.40
Nitrogen (N)	44.35
Potassium (K)	63.70

*EC in soil paste extract; pH in soil: water (1:2.5) suspension

Recorded data

Wheat measurements

Days to 50% of heading was recorded in each subplot. A random sample of 10 plants per subplot in each replicate was collected to assess the morpho-physiological characteristics of wheat cultivars. The following parameters were measured: flag leaf area (cm^2), plant height (cm), and flag leaf chlorophyll content (using a SPAD-502 meter). A handheld infrared thermometer was used to measure canopy temperature depression (CTD), which is the difference between the ambient air temperature and the canopy temperature in degrees Celsius (Fischer *et al.,* 1998). Number of spikes/m^2, number of grains/spike, and 1000-grain weight (g) were recorded. Grain, straw, and biological yields were also estimated and expressed in tons per hectare (t ha^{-1}).

N, P, and K in grains and straw

At physiological maturity, five randomly selected guarded plants were harvested from each subplot by cutting at the soil surface. The plants were combined into a single sample per subplot and separated into straw (comprising leaves, stems, and spike residues) and grains. These samples were oven-dried at 70 °C until they reached a constant weight, after which each component was weighed separately. The dried samples were then ground into a fine powder. Nitrogen content in the grains and straw was determined using the micro Kjeldahl method, and the results were multiplied by 5.75 to calculate the percentage of crude protein. The plant samples were also analyzed for P and K content.

N-uptake and use efficiencies

Nitrogen uptake in both straw and grains was calculated. Grain N uptake (kg ha^{-1}) was determined by multiplying the grain yield by the nitrogen percentage in the grains. The following nitrogen use efficiency parameters, based on kg ha^{-1}, were calculated according to the method outlined by Fageria *et al.* (2011b):

1- Grain N-uptake (GNU, kg ha^{-1}) = Grain N content×grain yield (kg ha^{-1})

2- Straw N-uptake (SNU, kg ha^{-1}) = Straw N content×straw yield (kg ha^{-1})

3- Total N-uptake (TNU, kg ha^{-1}) = Grain N-uptake + straw N-uptake (kg ha^{-1})

4- Apparent Recovery Efficacy (ARE %) is the quantity of nutrient uptake per unit of nutrient applied. ARE = [Total N-uptake (kg ha^{-1}) of the treatment - total N-uptake of the control]/ [Total applied N (kg ha^{-1})] ×100.

5- Physiological Efficiency (PE kg kg^{-1}) is the biological yield per unit of nutrient uptake. PE = [Biological yield (kg) of the treatment - Biological yield (kg) of the control]/ [applied N (kg ha^{-1}) - total N-uptake (kg ha^{-1}) of the control].

6- Agronomic efficiency (AE kg kg^{-1}) is the economic production obtained per unit of nutrient applied. AE = [Grain yield (kg) of the treatment - grain yield (kg) of the control]/ [applied N (kg ha^{-1}) for the treatment].

7- Agro-physiological efficiency (APE, kg kg^{-1}) expresses the efficiency of a unit of N-uptake from applied N fertilizer in building up grain yield.

APE = Gf - Gu/ Ntf - Ntu

Gf is the grain yield of fertilized plants (kg), Gu is the grain yield of unfertilized plants (kg), Ntf is nutrient uptake by straw and grains in the fertilized plants (kg), and Ntu is nutrient uptake by straw and grains in unfertilized plants (kg). Nitrogen utilization efficiency (NUtE, kg kg^{-1}) is expressed as the ratio of grain yield to above-ground N-uptake. NUtE= Grain yield (kg) / above-ground N-uptake (Moll *et al.*,1982).

8- Nitrogen use efficiency (NUE, kg kg^{-1}) is the ratio of grain yield to available N from the soil and applied fertilizer. NUE = Grain yield (kg) / available N from the soil and fertilizer (kg) (Ladha *et al.,* 2005).

N stress tolerance measurements

A- Relative increase of grain yield % = [(Yt - Ys)/ Ys] ×100 (Rybiñski *et al.,* 2003)

B- Nitrogen sensitivity Index= [1-(Ys/Yt)]/SI

SI= [1-$\bar{Y}$s/$\bar{Y}$t] (Fischer and Wood 1979)

C- Tolerance Index = (Yt - Ys) (Rosielle and Hamblin, 1981)

C- Nitrogen stress sensitivity percentage index (NSSPI)= [$(Yt - Ys)/2(\bar{Y}t)$] ×100. (Moosavi *et al.,* 2008). Where Yt is the grain yield of the cultivar under treatment. Ys is the grain yield of the cultivar under stress. $\bar{Y}$t is the average grain yield of all cultivars under N treatment, and $\bar{Y}$s is the average grain yield of all cultivars under N stress.

Statistical procedure

The Least Significant Differences test was used at a 0.05 probability level to determine significant differences among treatment means. Principal component and heatmap analyses were generated using R statistical software. Factor analysis was conducted following the methods outlined by Cattell (1965) and Walton (1972).

Results

Phenological and morpho-physiological characteristics

The study revealed significant differences in days to heading across different N levels (Table 2). Increasing nitrogen levels from 0 to 288 kg N ha^{-1} significantly delayed days to heading. Among the wheat cultivars studied, 'Sakha-95' exhibited the earliest heading time at 77.75 days, significantly earlier than 'Giza-171' and 'Misr-3', with similar heading times of 79.17 and 78.67 days, respectively. Moreover, the interaction between N levels and cultivars was statistically significant. The earliest heading was observed in 'Sakha-95' at

76.33 days when no nitrogen or 96 kg N ha^{-1} was applied, while the latest heading occurred in 'Giza-171' at 81.00 days with 288 kg N ha^{-1}. Nitrogen levels also significantly influenced key morpho-physiological traits such as chlorophyll content, canopy temperature depression (CTD) at the milk stage, and flag leaf area (Table 2). Both chlorophyll content and flag leaf area increased significantly with high N levels, from 44.68 to 54.60 SPAD and 28.05 to 33.95 cm^2, respectively. CTD showed a slight decrease as nitrogen levels increased, with values ranging from -2.86 °C at N0 to -3.06 °C at N288, indicating a better thermal environment under high N applications. Among the cultivars, 'Sakha-95' had the highest chlorophyll content at 51.39 SPAD. 'Giza-171' and 'Sakha-95' also demonstrated superior CTD values of -3.34 °C and -3.32 °C, respectively, compared to 'Misr-3', which had a significantly higher CTD of -2.21 °C. Additionally, 'Giza-171' had the largest flag leaf area at 36.63 cm^2. The interaction between nitrogen levels and cultivars was significant for all three traits. The optimal values for chlorophyll content (57.27 SPAD), flag leaf area (38.38 cm^2), and CTD (-3.47 °C) were achieved with the application of 288 kg N ha^{-1} on 'Giza-171'.

Table 2. Effect of nitrogen levels on days to heading, chlorophyll content, canopy temperature depression, and flag leaf area in three bread wheat cultivars grown in salt-affected soil

Studied factors		Days to heading	Chlorophyll content (SPAD)	Canopy temperature depression (°C)	Flag leaf area (cm^2)
Nitrogen level (N)					
0 kg N ha^{-1}		77.11 c	44.68 d	-2.86 b	28.05 d
96 kg N ha^{-1}		77.67 bc	48.86 c	-2.95 ab	30.35 c
192 kg N ha^{-1}		78.78 b	51.29 b	-2.96 ab	32.23 b
288 kg N ha^{-1}		80.56 a	54.60 a	-3.06 a	33.95 a
Wheat cultivar (C)					
'Giza-171'		79.17 a	50.19 b	-3.34 a	36.63 a
'Sakha-95'		77.75 b	51.39 a	-3.32 a	29.94 b
'Misr-3'		78.67 a	47.98 c	-2.21 b	26.87 c
Interaction (N×C)					
0 kg N ha^{-1}	'Giza-171'	78.33 bc	41.66 f	-3.17 a	34.36 b
	'Sakha-95'	76.33 d	47.87 d	-3.33 a	26.65 e
	'Misr-3'	76.67 d	44.50 e	-2.07 b	23.13 f
96 kg N ha^{-1}	'Giza-171'	78.67 bc	49.27 d	-3.37 a	36.50 a
	'Sakha-95'	76.33 d	51.70 c	-3.33 a	29.89 d
	'Misr-3'	78.00 c	45.60 e	-2.24 b	24.67 f
192 kg N ha^{-1}	'Giza-171'	78.67 bc	52.57 bc	-3.37 a	37.27 a
	'Sakha-95'	78.33 bc	52.07 c	-3.37 a	30.53 d
	'Misr-3'	79.33 b	49.23 d	-2.13 b	28.90 d
288 kg N ha^{-1}	'Giza-171'	81.00 a	57.27 a	-3.47 a	38.38 a
	'Sakha-95'	80.00 ab	53.93 b	-3.33 a	32.69 bc
	'Misr-3'	80.67 a	52.60 bc	-2.39 b	30.78 d

Means with different letters are significantly different according to the least significant differences test ($P < 0.05$)

Yield and its attributes

The results presented in Table 3 demonstrated significant differences among N levels with respect to grain, straw, and biological yields, as well as key yield-related attributes, including plant height, number of spikes per plant, number of non-productive tillers per plant, number of spikes per square meter, number of grains per spike, 1000-grain weight, and overall grain yield (tons ha^{-1}) at harvest. Plant height significantly responded to varying N levels, increasing from 97.16 cm at N0 to 100.55 cm at N96 and 99.54 cm at N192 before slightly decreasing to 95.81 cm at N288. This trend is closely related to number of spikes per plant, which increased consistently with higher N levels, from 1.64 spikes/plant at N0 to 2.48 spikes/plant at N288. Similarly, number of spikes per square meter also increased, from 347.89 spikes/m^2 at N0 to 417.11 spikes/m^2 at N288. Number of grains per spike increased significantly with high N level, from 53.89 at N0 to 62.88 at N288. 1000-grain weight followed a similar pattern, with slight variations: 56.48 g at N0, 58.34 g at N96, reaching the peak at 58.77 g at N192, and slightly decreasing to 58.02 g at N288. Grain, straw, and biological yields significantly increased with high N levels. Grain yield increased from 4.58 ton ha^{-1} at N0 to 7.93 ton ha^{-1} at N288, straw yield increased from 6.55 ton ha^{-1} at N0 to 12.94 ton ha^{-1} at N288, and biological yield increased from 11.13 ton ha^{-1} at N0 to 20.87 ton ha^{-1} at N288.

Table 3. Impact of nitrogen fertilization levels on yield traits of three bread wheat cultivars under salinity stress

Studied factors		**Plant height (cm)**	**No. of spikes/ plant**	**No. of spikes/ m^2**	**No. of non-productive tillers/ plant**	**No. of grains /spike**	**1000-grain weight (g)**	**Grain yield (ton ha^{-1})**	**Straw yield (ton ha^{-1})**	**Biological yield (ton ha^{-1})**
Nitrogen level (N)										
0 kg N ha^{-1}		97.16 b	1.64 d	347.89 d	0.45 a	53.89 d	56.48 b	4.58 d	6.55 d	11.13 d
96 kg N ha^{-1}		100.55 a	1.91 c	365.00 c	0.37 ab	57.26 c	58.34 a	5.43 c	8.01 c	13.43 c
192 kg N ha^{-1}		99.54 a	2.35 b^{-1}	392.00 b	0.30 b	61.34 b	58.77 a	7.81 b	10.98 b	18.78 b
288 kg N ha^{-1}		95.81 b	2.48 a	417.11 a	0.23 b	62.88 a	58.02 a	7.93 a	12.94 a	20.87 a
Wheat cultivar (C)										
'Giza-171'		99.90 b	2.02 b	351.83 c	0.28 b	62.89 b	62.31 a	6.28 b	9.62 a	15.90 ab
'Sakha-95'		100.82 a	2.14 a	397.42 a	0.35 a	65.23 a	56.89 b	6.72 a	9.81 a	16.53 a
'Misr-3'		94.08 c	2.12 a	392.25 b	0.38 a	48.41 c	54.51 c	6.32 b	9.41 a	15.73 b
Interaction (N×C)										
0 kg N ha^{-1}	'Giza-171'	98.80 cd	1.83 d	335.00 j	0.40 ab	59.33 f	61.40 b	4.50 g	6.50 d	11.00 e
	'Sakha-95'	97.10 d	1.60 e	337.00 j	0.53 a	52.27 g	54.50 e	4.66 f	6.57 d	11.23 e
	'Misr-3'	95.57 e	1.50 e	371.67 f	0.42 ab	50.07 h	53.53 e	4.59 fg	6.57 d	11.16 e
96 kg N ha^{-1}	'Giza-171'	100.85 b	1.83 d	344.67 i	0.37 b	63.00 d	62.07 ab	5.23 e	8.10 c	13.33 cd
	'Sakha-95'	103.67 a	1.77 d	392.67 e	0.33 bc	62.93 d	56.60 d	5.85 d	8.57 c	14.42 c
	'Misr-3'	97.13 d	2.13 c	357.67 h	0.40 bc	45.83 j	56.37 d	5.20 e	7.35 cd	12.55 d
192 kg N ha^{-1}	'Giza-171'	101.08 b	2.13 c	361.00 h	0.23 c	61.53 e	63.27 a	7.67 c	11.03 b	18.70 b
	'Sakha-95'	104.60 a	2.62 a	400.00 d	0.28 bc	73.87 a	59.60 c	8.11 a	11.27 b	19.37 b
	'Misr-3'	92.93 f	2.29 b	415.00 c	0.37 b	48.63 i	53.43 e	7.64 c	10.63 b	18.28 b
288 kg N ha^{-1}	'Giza-171'	92.87 f	2.30 b	366.67 g	0.13 c	67.70 c	62.50 ab	7.72 bc	12.87 a	20.59 ab
	'Sakha-95'	97.90 cd	2.57 a	460.00 a	0.23 c	71.83 b	56.87 d	8.25 a	12.88 a	21.12 a
	'Misr-3'	90.68 g	2.57 a	424.67 b	0.33 bc	49.10 h	54.70 e	7.84 b	13.07 a	20.91 a

Means with different letters are significantly different according to the Least significant differences test ($P < 0.05$

Significant differences (Table 3) were also observed among the three wheat cultivars in yield and its contributing traits. 'Sakha-95' stood out for its performance, producing the tallest plants (100.82 cm), the highest number of spikes per plant (2.14), the most spikes per square meter (397.4 spikes/m^2), and the greatest number of grains per spike (65.23). 'Sakha-95' also achieved the highest grain yield (6.72 tons ha^{-1}), straw yield (9.81 tons ha^{-1}), and biological yield (16.53 tons ha^{-1}). On the other hand, 'Giza-171' excelled in 1000-grain weight, with a peak value of 62.31 g and had the lowest number of non-productive tillers per plant (0.28)**.** The interaction effect between N levels and cultivars was significant for yields and related attributes. The highest number of spikes per square meter (460 spikes/m^2), grain yield (8.25 tons ha^{-1}), and biological yield (21.12 tons ha^{-1}) were recorded for 'Sakha-95' at the highest N application rate of 288 kg N ha^{-1}. Similarly, the tallest plants

(104.60 cm), the greatest number of spikes per plant (2.62), and the highest number of grains per spike (73.87) were observed in 'Sakha-95' at 192 kg N ha^{-1}. 'Giza-171' achieved the highest 1000-grain weight (63.27 g) at 192 kg N ha^{-1}, while the lowest number of non-productive tillers per plant (0.13) was recorded for 'Giza-171' at 288 kg N ha^{-1}. Furthermore, 'Misr-3' achieved the highest straw yield (13.07 tons ha^{-1}) at 288 kg N ha^{-1}**.**

Nutrient content

As shown in Table 4, significant variations were observed across different nitrogen (N) levels for phosphorus (P) and potassium (K) content in both grains and straw. Phosphorus content in grains increased from 0.22% at N0 to 0.43% at N288, and in straw, it ranged from 0.27% at N0 to 0.39% at N288. Potassium content in grains also showed a slight increase with higher N levels ranging from 0.219% at N0 to 0.277% at N288.

Table 4. Impact of nitrogen fertilization levels on phosphorus, potassium, and nitrogen contents in grains and straw at harvest for three bread wheat cultivars under salinity stress

Studied factors		P in grains (%)	P in Straw (%)	K in grains (%)	K in straw (%)	N in grains (%)	N in Straw (%)
Nitrogen level (N)							
0 kg N ha^{-1}		0.22 c	0.27 c	0.219 b	1.89 b	1.74 d	0.598 b
96 kg N ha^{-1}		0.30 b	0.31 bc	0.231 ab	1.89 b	1.85 c	0.629 b
192 kg N ha^{-1}		0.31 b	0.32 b	0.254 ab	1.97 ab	1.98 b	0.651 ab
288 kg N ha^{-1}		0.43 a	0.39 a	0.277 a	2.13 a	2.09 a	0.725 a
Wheat cultivar (C)							
'Giza-171'		0.30 b	0.34 b	0.234 b	2.03 a	1.93 ab	0.662 a
'Sakha-95'		0.37 a	0.25 c	0.258 a	1.88 b	1.85 b	0.624 a
'Misr-3'		0.27 b	0.38 a	0.245 ab	1.99 ab	1.96 a	0.667 a
Interaction (N×C)							
0 kg N ha^{-1}	'Giza-171'	0.22 cd	0.24 c	0.210 a	1.94 ab	1.76 b	0.603 b
	'Sakha-95'	0.29 bc	0.19 c	0.227 a	1.88 ab	1.67 b	0.505 b
	'Misr-3'	0.17 d	0.37 b	0.220 a	1.84 ab	1.78 b	0.686 ab
96 kg N ha^{-1}	'Giza-171'	0.21 cd	0.33 b	0.216 a	2.01 ab	1.85 b	0.658 ab
	'Sakha-95'	0.34 b	0.21 c	0.250 a	1.68 b	1.75 b	0.611 b
	'Misr-3'	0.26 c	0.39 ab	0.227 a	1.99 ab	1.95 ab	0.617 ab
192 kg N ha^{-1}	'Giza-171'	0.27 bc	0.34 b	0.250 a	2.02 ab	1.97 ab	0.644 ab
	'Sakha-95'	0.41 ab	0.24 c	0.260 a	1.92 ab	1.95 ab	0.665 ab
	'Misr-3'	0.24 cd	0.38 b	0.253 a	1.97 ab	2.02 ab	0.644 ab
288 kg N ha^{-1}	'Giza-171'	0.42 ab	0.44 a	0.263 a	2.17 a	2.14 a	0.742 a
	'Sakha-95'	0.43 a	0.34 b	0.293 a	2.07 a	2.04 ab	0.714 ab
	'Misr-3'	0.43 a	0.39 ab	0.277 a	2.14 a	2.07 a	0.721 ab

Means with different letters are significantly different according to the Least significant differences Test ($P < 0.05$)

High external sodium (Na+) concentrations can inhibit potassium absorption, leading to lower potassium accumulation in the roots and, subsequently, in the grains. No significant differences were observed for potassium content in straw between N0, N96, and N192. However, a substantial increase was observed at N288, where K content reached 2.13%, compared to 1.89% and 1.97% at the low N levels (Table 4). Significant differences were also recorded among the wheat cultivars tested. For phosphorus content in grains, 'Sakha-95' had the highest value at 0.37%, while 'Misr-3' had the lowest at 0.27%. Conversely, 'Misr-3' had the highest phosphorus content in straw at 0.38%, compared to 'Sakha-95', which had the lowest at 0.25%. Regarding potassium content, 'Sakha-95' outperformed the other cultivars in grains with a content of 0.258%, while 'Giza-171' had the highest potassium content in the straw (2.03%), compared to 'Sakha-95' (1.88%). The interaction between N levels and cultivars significantly impacted P content in grains and straw and K content in straw only. The highest phosphorus (0.43%) and potassium (0.293%) contents in grains were achieved when ‘Sakha-95’ received 288 kg N ha^{-1}. Similarly, the maximum phosphorus (0.44%) and potassium (2.17%) contents in straw were observed when ‘Giza-171’ was fertilized with 288 kg N ha^{-1}.

Nitrogen-related parameters

Table 5 shows significant differences across N levels for various nitrogen-related parameters, including nitrogen content in grains and straw, grain and straw protein content, grain and straw nitrogen uptake, and total nitrogen uptake. The trends for these characteristics were consistent, whether considering the effect of nitrogen fertilizer levels, cultivar differences, or their interactions**.** Nitrogen content in grains increased from 1.74% at N0 to 2.09% at N288, while in straw, it ranged from 0.598% at N0 to 0.725% at N288.

Table 5. Impact of nitrogen fertilization levels on nitrogen content in grain and straw for three bread wheat cultivars under salinity stress

Studied factors		Grain protein (%)	Straw protein (%)	Grain N-uptake (%)	Straw N-uptake (%)	Total N-uptake (kg N ha^{-1})
Nitrogen level (N)						
0 kg N ha^{-1}		9.99 d	3.44 b	79.57 d	39.15 d	118.72 d
96 kg N ha^{-1}		10.62 c	3.62 b	100.17 c	50.33 c	150.51 c
192 kg N ha^{-1}		11.39 b	3.74 ab	154.52 b	71.48 b	226.003 b
288 kg N ha^{-1}		11.99 a	4.17 a	165.26 a	94.00 a	259.14 a
Wheat cultivar (C)						
‘Giza-171’		11.10 b	3.81 a	123.06 b	64.75 a	187.82 ab
‘Sakha-95’		10.65 c	3.58 a	126.66 a	63.22 a	189.75 a
‘Misr-3’		11.26 a	3.83 a	124.93 ab	63.27 a	188.21 b
Interaction (N×C)						
0 kg N ha^{-1}	‘Giza-171’	10.11 b	3.47 b	79.20 f	39.20 f	118.40 i
	‘Sakha-95’	9.61 b	2.91 b	77.82 f	33.18 g	111.00 j
	‘Misr-3’	10.25 b	3.95 ab	81.70 f	45.07 e	126.77 h
96 kg N ha^{-1}	‘Giza-171’	10.61 b	3.80 ab	96.75 e	53.30 d	150.05 f
	‘Sakha-95’	10.05 b	3.51 b	102.38 d	52.36 d	154.74 e
	‘Misr-3’	11.21 ab	3.55 ab	101.40 d	45.35 e	146.75 g
192 kg N ha^{-1}	‘Giza-171’	11.34 ab	3.70 ab	151.10 c	71.03 bc	222.13 d
	‘Sakha-95’	11.21 ab	3.82 ab	158.15 bc	74.95 b	233.09 c
	‘Misr-3’	11.63 ab	3.70 ab	154.33 c	68.46 c	222.79 d
288 kg N ha^{-1}	‘Giza-171’	12.32 a	4.27 a	165.21 ab	95.50 a	260.70 a
	‘Sakha-95’	11.73 ab	4.09 ab	168.30 a	91.89 a	260.19 a
	‘Misr-3’	11.93 a	4.14 ab	162.29 b	94.23 a	256.52 b

Means with different letters are significantly different according to the Least significant differences test (P < 0.05

Grain protein content also increased with higher N levels, from 9.99% at N0 to 11.99% at N288, and straw protein content followed a similar pattern, rising from 3.44% at N0 to 4.17% at N288. Additionally, grain nitrogen uptake increased considerably, from 79.57 kg N ha^{-1}at N0 to 165.26 kg N ha^{-1}at N288, while straw nitrogen uptake rose from 39.15 kg N ha^{-1} at N0 to 94.00 kg N ha^{-1} at N288. Total nitrogen uptake, involving both grain and straw, showed a substantial increase from 118.72 kg N ha^{-1} at N0 to 259.14 kg N ha^{-1} at N288. Among the three wheat cultivars, ‘Misr-3’ exhibited the highest nitrogen content in grains (1.96%), straw nitrogen content (0.667%), straw protein content (3.83%), and grain protein content (11.26%). However, ‘Sakha-95’ excelled in grain nitrogen uptake (126.66 kg N ha^{-1}) and total nitrogen uptake (189.75 kg N ha^{-1}). ‘Giza-171’ showed superior straw nitrogen uptake at 64.75 kg N ha^{-1}. The interaction between N levels and cultivars significantly affected nitrogen content, nitrogen uptake, and protein content. The highest values for nitrogen content in grains (2.14%), straw nitrogen content (0.742%), grain protein content (12.32%), straw protein content (4.27%), and straw nitrogen uptake (95.50 kg N ha^{-1}) were achieved when 'Giza-171' was treated with 288 kg N ha^{-1}. Additionally, 'Sakha-95' reached the highest grain nitrogen uptake (168.30 kg N ha^{-1}) and total nitrogen uptake (260.19 kg N ha^{-1}) at the same N level.

Nitrogen use efficiency components

Nitrogen use efficiency components, including physiological efficiency (PE), agronomic efficiency (AE), agro-physiological efficiency (APE), and apparent recovery efficiency (ARE) varied significantly among the wheat genotypes at different nitrogen (N) levels, as presented in Table 6.

Table 6. Nitrogen use efficiencies of three bread wheat cultivars under different nitrogen levels: Physiological efficiency (PE), agronomic efficiency (AE), agro-physiological efficiency (APE), apparent recovery efficiency (ARE), nitrogen utilization efficiency (NUtE), and nitrogen use efficiency (NUE)

Studied factors		**PE (kg kg^{-1})**	**AE (kg kg^{-1})**	**APE (kg kg^{-1})**	**ARE (%)**	**NUtE (kg N ha^{-1})**	**NUE (kg kg^{-1})**
Nitrogen level (N)							
0 kg N ha^{-1}						38.73 a	103.33 a
96 kg N ha^{-1}		72.04 a	8.78 c	26.93 b	33.11 c	36.03 b	38.66 b
192 kg N ha^{-1}		71.67 a	16.79 a	30.19 a	55.87 a	34.54 c	39.75 b
288 kg N ha^{-1}		69.60 b	11.64 b	23.91 c	48.75 b	30.63 d	23.87 c
Wheat cultivar (C)							
'Giza-171'		71.74 a	11.76 b	25.41 b	45.47 b	34.25 b	50.24 b
'Sakha-95'		68.66 b	14.28 a	26.51 b	53.65 a	36.57 a	53.21 a
'Misr-3'		72.92 a	11.17 b	29.11 a	38.62 c	34.12 b	50.75 ab
Interaction (N×C)							
0 kg N ha^{-1}	'Giza-171'					38.01 ab	101.45 a
	'Sakha-95'					41.98 a	105.07 a
	'Misr-3'					36.20 c	103.49 a
96 kg N ha^{-1}	'Giza-171'	73.60 bc	7.60 d	23.06 f	32.98 f	34.86 cd	37.26 bc
	'Sakha-95'	72.94 c	12.40 c	27.21 d	45.56 e	37.81 ab	41.68 b
	'Misr-3'	69.58 c	6.35 d	30.53 b	20.81 g	35.43 cd	37.05 bc
192 kg N ha^{-1}	'Giza-171'	74.23 b	16.51 b	30.56 b	54.03 b	34.53 cd	39.06 b
	'Sakha-95'	66.75 e	17.97 a	28.26 cd	63.59 a	34.79 cd	41.3 b
	'Misr-3'	74.05 b	15.89 b	31.77 a	50.01 cd	34.29 cd	38.91 b
288 kg N ha^{-1}	'Giza-171'	67.39 d	11.18 c	22.63 f	49.41 d	29.61 d	23.22 c
	'Sakha-95'	66.29 e	12.47 c	24.06 ef	51.80 c	31.71 d	24.82 c
	'Misr-3'	75.14 a	11.28 c	25.05 e	45.05 e	30.56 d	23.58 c

Means with different letters are significantly different according to the Least Significant Differences Test ($P < 0.05$)

PE reflects the ability of the plant to convert absorbed nitrogen into biomass, decreased progressively with increasing N levels, showing values of 72.04, 71.67, and 69.60 at N96, N192, and N288, respectively. In contrast, AE, APE, and ARE initially increased with nitrogen application, peaking at N192 before declining at the N288 level. Specifically, AE values rose from 8.78 at N0 to 16.79 at N192 before dropping to 11.64 at N288. Similarly, APE and ARE values followed this trend, with APE reaching 30.19 at N192, then decreasing to 23.91 at N288, and ARE peaking at 55.87% at N192 before declining to 48.75% at N288. NUtE and NUE were higher at lower N level (N0) than at higher N level (N288), as shown in Table 6. NUtE decreased from 38.73 at N0 to 30.63 at N288, and NUE declined greatly from 103.33 at N0 to 23.87 at N288. Significant differences were also detected among wheat cultivars regarding their nitrogen use efficiency components. Misr-

3 exhibited the highest PE (72.92), while 'Sakha-95' showed the lowest (68.66). Conversely, 'Sakha-95' excelled in AE (14.28) and ARE (53.65%). 'Misr-3' led in APE (29.11), while 'Giza-171' recorded the lowest at 25.41. Regarding NUtE and NUE, 'Sakha-95' again performed best with values of 36.57 and 53.21, respectively. The interaction between nitrogen levels and cultivars significantly impacted all nitrogen use efficiency components. The highest PE (75.14) was recorded for 'Misr-3' at 288 kg N ha^{-1}. 'Sakha-95' achieved the highest values for AE (17.97) and ARE (63.59) at 192 kg N ha $^{-1}$, while 'Misr-3' exhibited the best APE (31.77) at the same N level. 'Sakha-95' also showed the highest NUtE (41.98) and NUE (105.07) at N0**.**

Nitrogen stress tolerance measurements

As illustrated in Figure 1A, the relative increase in grain yield (%) for three bread wheat cultivars, 'Giza-171', 'Sakha-95', and 'Misr-3', showed a significant growing trend with increasing nitrogen levels. The relative increase in grain yield for 'Giza-171' was 16.2%, 70.4%, and 71.6% for N96, N192, and N288 compared to N0, respectively. 'Sakha-95' increased 25.5%, 74.0%, and 77.0%, while 'Misr-3' recorded 18.6%, 66.5%, and 70.8% across the same N levels. On average, the relative increase across all cultivars was 20.1%, 70.3%, and 73.1% for N96, N192, and N288 compared to N0, respectively, underscoring the crucial role of nitrogen in boosting grain yields. Among the cultivars, 'Sakha-95' exhibited the highest average relative increase at 58.9%, followed by 'Giza-171' at 52.7% and 'Misr-3' at 51.9%.

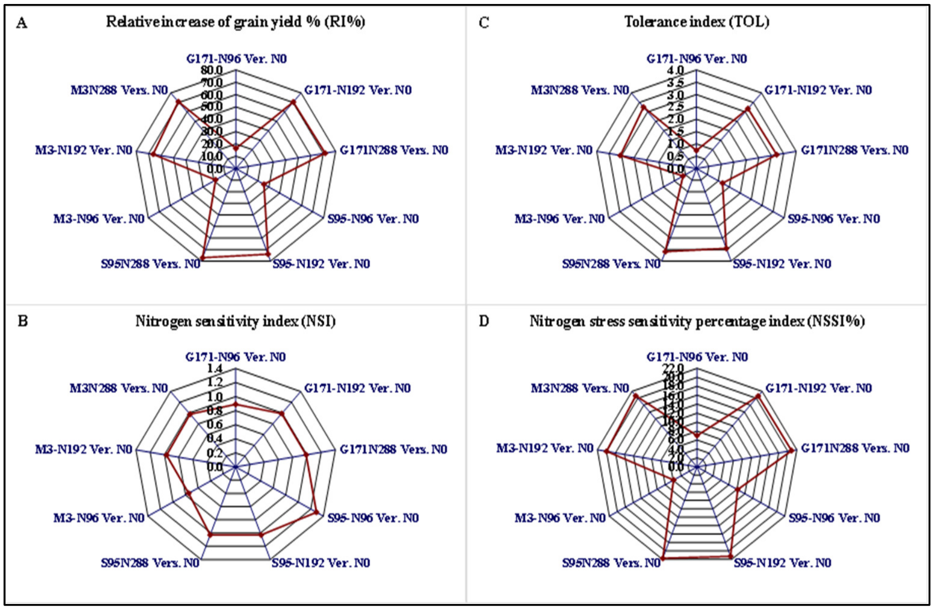

Figure 1. Nitrogen stress tolerance measurements: relative increase of grain yield (A), nitrogen sensitivity index (B), tolerance index (C), and nitrogen stress sensitivity percentage index (D)

Further analysis, depicted in Figures 1B, 1C, and 1D, presents Nitrogen Sensitivity Index, Tolerance Index, and Nitrogen Stress Sensitivity Percentage Index at different nitrogen levels compared to N0, aiming to identify cultivars that are either tolerant or sensitive to nitrogen stress, whether due to deficiency or excess**.** 'Misr-3' appeared to be the most tolerant cultivar to nitrogen deficiency stress, followed closely by 'Giza-171', based on the Nitrogen Sensitivity Index, Tolerance Index, and NSSPI at N96 versus N0. In contrast, 'Sakha-95' was identified as the most sensitive cultivar under nitrogen-deficient conditions.

Interrelationships among assessed treatments and studied characters

Principal component analysis (PCA) explored the relationships among the assessed wheat genotype treatments and the studied traits (Figure 2). The first two principal components (PCs) accounted for 97.15%

of the total variability, with PC1 explaining 60.45% of the variation. PC1 was primarily associated with yield performance of evaluated treatments. High-yielding genotypes under high nitrogen level were positioned on the positive side of PC1, while those with the lowest performance under unfertilized conditions were located on the extreme negative side. Specifically, the treatments S-95-N288 and G1712-288 were situated on the positive side of PC1, showing strong associations with traits such as grain yield (t ha^{-1}), biological yield (t ha^{-1}), straw nitrogen uptake, spikes/m^2, phosphorus content in grains, chlorophyll content, potassium content in straw, and protein content in straw**.** In contrast, NUE and NUtE were negatively correlated with yield traits, as the highest values for these efficiencies were observed in the low-yielding treatments S95-N0 and G171-N0**.**

PC2 explained 18.70% of the variation was related to canopy temperature depression and plant height. Treatments G171-N96 and S95-N96 were located on the opposite side of PC2, indicating a distinct relationship with these traits**.** Nutrient components; N, P, K, N uptake, protein content, chlorophyll content, and days to heading were positively associated with yield-related characteristics on the positive side of PC1. The interaction between genotypes and N levels exhibited significant variation in multidimensional space, with different distances and orientations in the PCA plot, indicating their diverse agronomic performance.

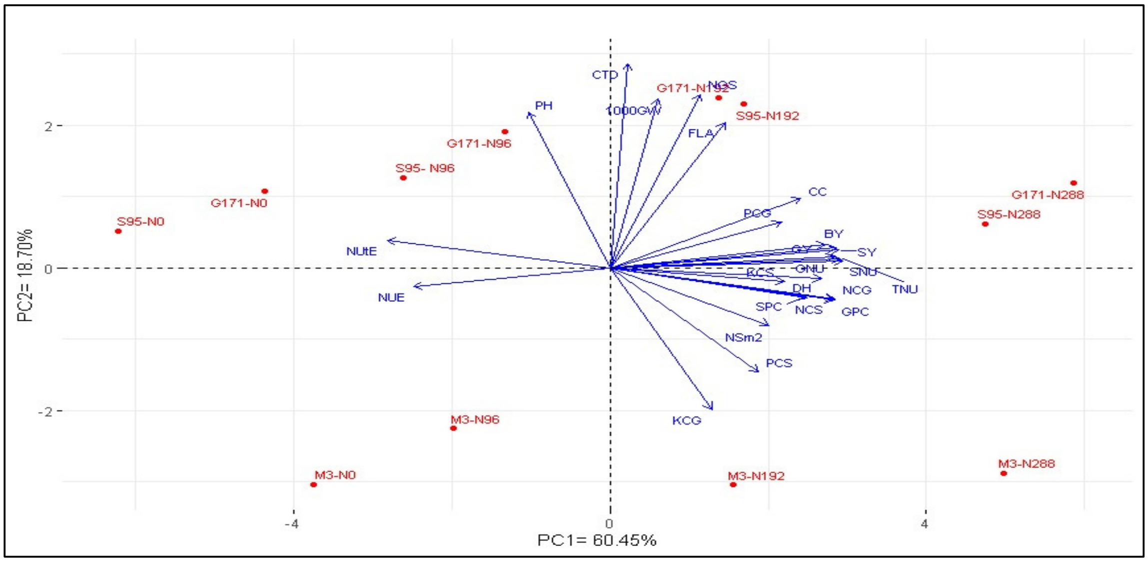

Figure 2. PCA biplot of the assessed wheat genotype treatments based on morpho-physiological, nutrient contents, yield performance, NUtE, and NUE of the assessed treatments.

DH: days to heading, NCG: nitrogen content in grains, NCS: nitrogen content in straw, PCG: phosphorus content in grains, PCS: phosphorus content in straw, KCG: potassium content in grains, KCS: potassium content in straw, GNU: grain nitrogen uptake, SNU: straw nitrogen uptake, TNU: total nitrogen uptake, GPC: grain protein content, SPC: straw protein content, GY: grain yield tonne ha^{-1}, SY: straw yield tonne ha^{-1}, BY: biological yield tonne ha^{-1}, CTD: canopy temperature depression, CC: chlorophyll content, FLA: flag leaf area, PH: plant height, NSm^2: number of spike m^{-2}, NGS: number of grains/spike, 1000 GW: 1000-grain weight, NUtE: nitrogen utilization efficiency, NUE: nitrogen use efficiency.

Additionally, a heatmap based on the studied traits separated the genotype treatments into distinct clusters (Figure 3). The treatment G171-N288 surpassed in traits of days to heading, K content in straw, N content in straw, straw protein content, P content in straw, N content in grains, grain protein content, straw yield, biological yield, total nitrogen uptake, grain yield, straw N uptake, chlorophyll content, number of grains per spike, 1000-grain weight, flag leaf area, optimal canopy temperature depression, and short plant height. Similarly, G95-N288 performed exceptionally well in many of these traits, with moderately high canopy temperature depression. M3-N288 also excelled in traits of K content in straw, N content in straw, straw protein content, N content in grains, and several yield components, though it showed late days to heading and low canopy temperature depression**.** On the other hand, treatments S-95-N0 and M3-N0 exhibited superior values in NUtE and NUE, as well as short plant height, with G171-N0 also excelling in NUtE, NUE, and short plant height**.** Previous studies have reported substantial differences in the behavior of wheat genotypes under varying nitrogen levels, particularly in relation to nutrient uptake and morpho-physiological traits linked to yield.

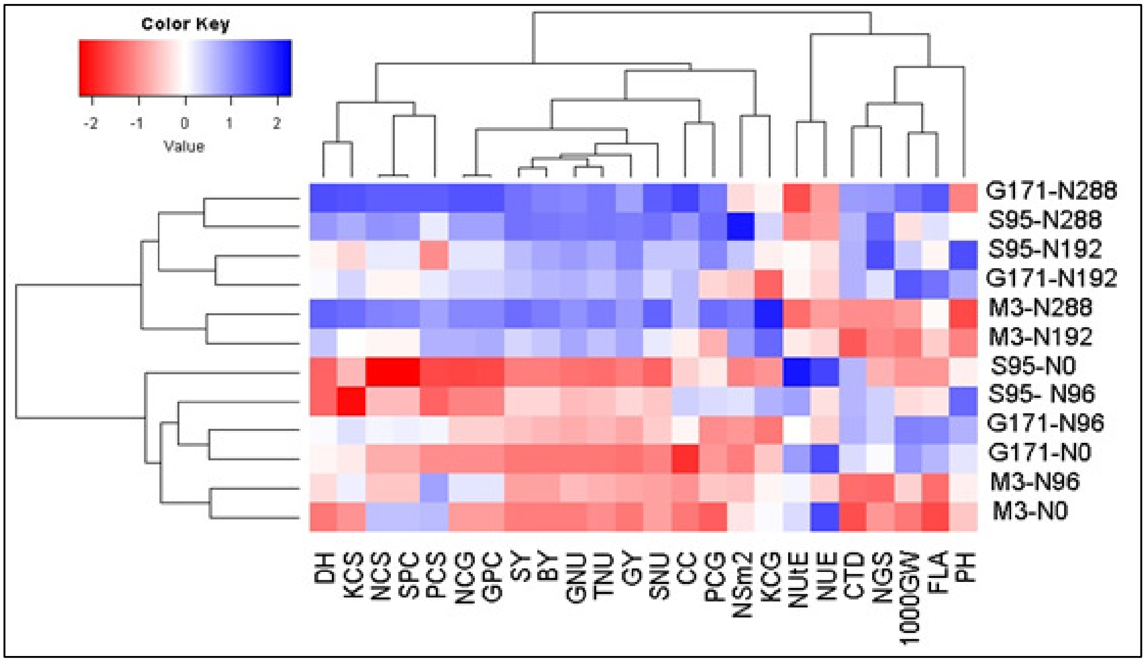

Figure 3. Heatmap of the assessed wheat genotype treatments based on morpho-physiological, nutrient contents, yield performance, NUtE, and NUE of the assessed treatments.

Red and blue colors imply low and high values for the corresponding parameters, respectively. DH: days to heading, NCG: nitrogen content in grains, NCS: nitrogen content in straw, PCG: phosphorus content in grains, PCS: phosphorus content in straw, KCG: potassium content in grains, KCS: potassium content in straw, GNU: grain nitrogen uptake, SNU: straw nitrogen uptake, TNU: total nitrogen uptake, GPC: grain protein content, SPC: straw protein content, GY: grain yield tonne ha^{-1}, SY: straw yield tonne ha^{-1}, BY: biological yield tonne ha^{-1}, CTD: canopy temperature depression, CC: chlorophyll content, FLA: flag leaf area, PH: plant height, NSm^{2}: number of spike m^{-2}, NGS: number of grains/spike, 1000 GW: 1000-grain weight, NUtE: nitrogen utilization efficiency, NUE: nitrogen use efficiency.

Factor analysis

Factor analysis is used to explore relationships among multiple dependent variables and to determine the nature of the independent variables that influence them, even when these variables are not directly measured. This method is particularly powerful in detecting fundamental multivariate structures**.** The results of the factor analysis for the nineteen studied characteristics are presented in Figure 4 and Table 7. The analysis grouped twenty-eight variables into four factors, accounting for 92.47% of the total variability**.** Factor 1 included eighteen variables, explaining 60.93% of the total variance, highlighting the importance of these traits in influencing wheat performance, particularly in yield and nitrogen uptake efficiency**.** Factor 2 consisted of four variables: flag leaf area, plant height, number of grains per spike, and 1000-grain weight. This factor accounted for 17.62% of the total variability, emphasizing the role of morphological traits in wheat productivity**.** Factor 3 contained two variables, potassium content in grains and NUtE, and explained 9.83% of the total variance. This factor underscored the significance of nutrient content and utilization efficiency in the overall performance of wheat genotypes**.** Factor 4 included a single variable, number of non-productive tillers per plant, accounting for 4.10% of the variance. This factor highlighted the impact of non-productive tillers on nitrogen use efficiency in wheat plants**.** The results highlighted the importance of phenological and morpho-physiological traits, nutrient components, nitrogen uptake, and yield-related traits, particularly those included in Factor 1 in enhancing NUE**.**

Table 7. Summary of factor loadings for key wheat traits influencing nitrogen use efficiency.

Variable	Loading	Percentage of total
Factor 1		60.93
Days to heading	0.896	5.73
Chlorophyll content	0.807	5.16
Canopy temperature depression	0.980	6.26
No. of spikes plant-1	0.873	5.58
No. of spikes m-2	0.672	4.29
Grain yield (tonne ha-1)	0.917	5.86
Straw yield (tonne ha-1)	0.974	6.22
Biological yield (tonne ha-1)	0.961	6.14
N content in grains	0.948	6.06
N content in straw	0.833	5.32
P content in grains	0.737	4.71
P content in straw	0.612	3.91
K content in straw	0.740	4.73
Grain protein content	0.947	6.05
Straw protein content	0.826	5.28
Grain N-uptake	0.956	6.11
Straw N-uptake	0.989	6.32
Total N- uptake	0.980	6.26
Factor 2		17.62
Flag leaf area	0.674	22.32
Plant height	0.736	24.37
No. of grains spike-1	0.806	26.69
1000-grain weight	0.804	26.62
Factor 3		9.83
K content in grains	0.423	64.48
NUtE	0.233	35.52
Factor 4		4.10
No. of non-productive tillers plant-1	0.224	
Cumulative variance		92.47

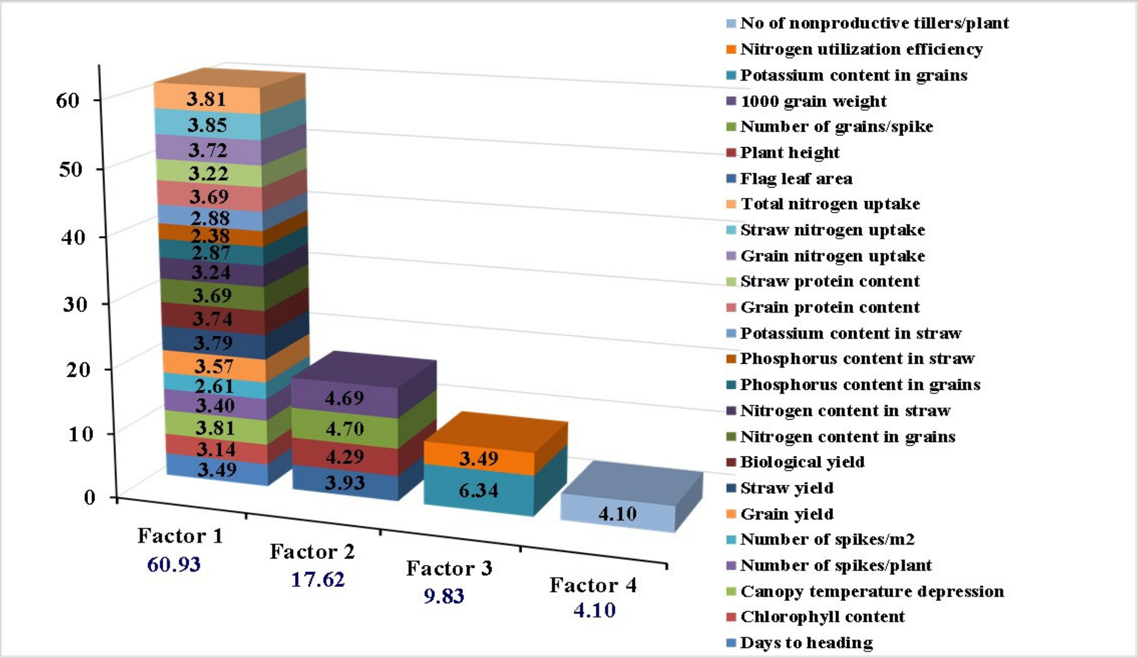

Figure 4. Factor loadings of studied wheat traits affect nitrogen use efficiency

Discussions

The results of this study provide significant insights into the effects of nitrogen levels on the morpho-physiological and yield-related characteristics of different wheat cultivars in salt-affected soils. The observed delay in heading time with increasing Nitrogen (N) levels, ranging from 77.1 to 80.6 days, is consistent with the role of nitrogen in promoting vegetative growth and cell elongation, thereby extending the period before heading. This delay is particularly important in optimizing the growth cycle to maximize yield, as prolonged vegetative growth can result in increased biomass and potential grain yield. The genetic variability among the studied cultivars, particularly the earlier heading of 'Sakha-95' compared to' Giza-171' and 'Misr-3', emphasized the importance of selecting appropriate cultivars based on specific agronomic goals and environmental conditions under salinity soils. The significant interaction between N levels and cultivars highlights the complex relationship between nitrogen availability and phenological development. For instance, the earliest heading observed in 'Sakha-95', with lower N levels, and the latest heading in 'Giza-171', with the highest N level, suggests that nitrogen management strategies should be modified based on used cultivars to optimize the overall growth cycle. These findings are in line with previous studies such as Lakew (2019) who documented the delaying effect of increased nitrogen on heading due to the extension of the vegetative growth phase. In addition, the study revealed significant impacts of nitrogen levels on key morpho-physiological characteristics, such as chlorophyll content, canopy temperature depression (CTD), and flag leaf area. The increase in chlorophyll content and flag leaf area with higher N levels is expected, given nitrogen crucial role in chlorophyll synthesis and vegetative growth (Kumar *et al*., 2017). These traits are critical for photosynthetic efficiency and overall plant vigor, contributing directly to yield potential. Higher nitrogen availability promotes leaf area development and increases chlorophyll content, both of which contribute to improved photosynthetic efficiency. This, in turn, leads to greater energy production and biomass accumulation, which supports better growth and higher yield potential. Nitrogen also plays a crucial role in the synthesis of key enzymes involved in metabolic processes, enhancing nutrient transport and assimilation within the plant

The relationship between nitrogen levels and salt stress is complex, as salt stress can significantly hinder nitrogen uptake and assimilation by disrupting root function and impairing nutrient transport. High salinity increases the concentration of sodium and chloride ions in the soil, which competes with essential nutrients like nitrogen for uptake by plant roots. This interference reduces NUE and NUtE limiting wheat growth and yield. However, this study indicated that adequate nitrogen availability can mitigate some of these negative effects. Higher nitrogen levels promote better root development, enhance osmotic regulation, and improve overall plant tolerance to salt stress. By improving the physiological processes related to nutrient uptake and assimilation, nitrogen helps sustain plant growth even under saline conditions. Furthermore, nitrogen fertilization can support the synthesis of osmotic regulators like proline, which help plants cope with the stress imposed by high salinity. This highlights the importance of nitrogen management in optimizing wheat productivity in salt-affected soils, as it can alleviate some of the physiological barriers to nutrient uptake and improve both yield and efficiency under saline conditions.

Among the cultivars, the superior performance of 'Sakha-95' in chlorophyll content and 'Giza-171' in flag leaf area and CTD further emphasized the importance of cultivar selection in nitrogen management. The interaction effects observed for all three traits, particularly the optimal performance of 'Giza-171' at the highest nitrogen level, suggest that this cultivar may have a higher NUE and be better adapted to intensive nitrogen management practices. This finding is crucial for developing cultivar specific nitrogen management strategies, which could lead to improved nitrogen use efficiency and enhanced yield potential under varying environmental conditions. These findings are supported by previous research, including Gheith *et al.,* (2022) and Awaad *et al.,* (2024), who also reported significant impacts of nitrogen on leaf area and chlorophyll content. However, the interaction effects observed in this study highlight the need for further research into the cultivar-specific responses to nitrogen, which could have significant implications for wheat production and sustainability.

The significant differences observed across various N levels for grain, straw, and biological yields, as well as key yield-related traits, highlighted the pivotal role of nitrogen in enhancing wheat productivity. The increase in plant height from 97.16 cm at N0 to a peak of 100.55 cm at N96, followed by a slight decline at the highest N level (N288), suggests that while nitrogen promotes vegetative growth, there may be a threshold beyond which additional N does not further increase plant height and may even have a diminishing effect. This trend is closely related to the number of spikes per plant and per square meter, which both increased with higher N levels. The compensatory effect observed between plant height and tillering capacity, where shorter plants produce more tillers, suggests a balancing mechanism in resource allocation that optimizes yield components under varying nitrogen conditions. These findings are consistent with previous research by Mandic *et al,.* (2015), who noted minor differences in plant height across different N levels. The increase in number of grains per spike and 1000-grain weight with higher N levels further illustrated the importance of nitrogen in enhancing reproductive growth and grain filling. However, the slight decrease in 1000-grain weight at the highest N level could indicate a trade-off between spikelet fertility and individual grain weight, where an increase in grain number may lead to a slight reduction in the size of individual grains. This observation aligns with Alley *et al.,* (2019), who emphasized the role of nitrogen in optimizing key yield components, including spikes per square meter, grains per spike, and kernel size. The substantial increases in grain, straw, and biological yields with higher nitrogen levels reflect the enhanced metabolic processes facilitated by nitrogen, which improves sink strength, carbon/nitrogen metabolism, and resource remobilization to the grain. The increase in grain yield from 4.58 tons ha^{-1} at N0 to 7.93 tons ha^{-1}at N288, alongside corresponding increases in straw and biological yields, confirms the significant impact of nitrogen on overall productivity. These findings are documented by Vicente *et al.,* (2024) who elucidated similar improvements in yield attributes with increased nitrogen application.

Among the three wheat cultivars studied, 'Sakha-95' demonstrated superior performance across several key yield attributes, including plant height, number of spikes per plant, spikes per square meter, and grains per spike, resulting in the highest grain, straw, and biological yields. The ability of this cultivar to produce more spikes and grains under high nitrogen levels indicates its strong response to nitrogen fertilization and its potential for high productivity under optimal nitrogen management. On the other hand, 'Giza-171' achieved the highest 1000-grain weight and lowest number of non-productive tillers, suggesting that this cultivar efficiently utilizes available resources, making it a good candidate for environments where resource efficiency is paramount. The significant interaction effects between N levels and cultivars confirm the necessity of cultivar-specific nitrogen management strategies. The highest yield attributes recorded for 'Sakha-95' at the highest N level, including the greatest number of spikes per square meter, grain yield, and biological yield. Similarly, the performance of 'Giza-171' in achieving the highest 1000-grain weight and lowest non-productive tillers at specific N levels further supports the need for nuanced nitrogen management to optimize yield outcomes. These findings are consistent with literature documenting the positive impact of nitrogen on yield and its components, as well as the variability in response due to cultivar selection and the interaction between nitrogen levels and cultivar characteristics. Studies by Mandic *et al.*, (2015) and El-Seidy *et al.*, (2017) have similarly reported linear increases in yield attributes with higher nitrogen levels and significant differences attributable to cultivar choice and the interaction between N levels and cultivar traits.

The observed increase in phosphorus content with higher nitrogen levels, ranging from 0.22% to 0.43% in grains and 0.27% to 0.39% in straw, suggests that elevated nitrogen levels enhance the plant ability to absorb and accumulate phosphorus. This is particularly important as phosphorus plays a crucial role in numerous physiological processes, including energy transfer, signal transduction, and the formation of nucleic acids, which are vital for plant growth and development. The role of potassium in regulating various physiological functions, such as photosynthesis, enzyme activation, and nutrient translocation, makes its adequate availability essential for optimizing crop yield. However, the findings also highlight the potential inhibitory effect of high external sodium (Na^+) concentrations on potassium absorption, which can negatively affect nutrient balance and grain quality, particularly under saline conditions. This is consistent with the observations of Rabhi *et al.*, (2009) who documented the detrimental impact of high Na^+ levels on potassium uptake and the resultant ionic imbalance in wheat. Interestingly, while potassium content in straw did not display significant differences between nitrogen levels (N0, N96, and N192), a substantial increase was observed at the highest nitrogen level (N288). This suggests that at higher nitrogen levels, there may be a threshold effect beyond which potassium uptake is significantly enhanced, potentially due to increased metabolic activity and nutrient demand associated with higher grain yields. The correlation between high nitrogen application and increased potassium content reinforces the importance of balanced nutrient management in achieving optimal crop performance under environmental stresses. The significant differences in nutrient content among wheat cultivars tested further emphasized the role of genetic factors in nutrient uptake and utilization. 'Sakha-95' exhibited the highest phosphorus and potassium content in grains and straw at specific nitrogen levels, demonstrating its superior nutrient use efficiency compared to the other cultivars. Conversely, 'Misr-3' showed the highest phosphorus content in straw, highlighting the variability in nutrient partitioning among different genotypes. These findings align with the work of Abd El-Azeiz *et al.*, (2021), who reported that increased nitrogen fertilizer rates enhance the content of key nutrients such as N, P, and K in wheat.

The results displayed significant impact of varying N levels on nitrogen-related parameters in wheat, including nitrogen content, protein content, and nitrogen uptake in both grains and straw. The observed increase in nitrogen content in grains from 1.74% at N0 to 2.09% at N288, and in straw from 0.598% to 0.725% across the same N levels, demonstrated nitrogen role in enhancing wheat nutrients. This increase in nitrogen content is crucial, as it directly correlates with improved grain quality and nutritional value, particularly in terms of protein content. Grain protein content increased significantly with higher nitrogen levels, from 9.99% at N0 to 11.99% at N288, and straw protein content followed a similar pattern, rising from 3.44% to 4.17%. These results are consistent with the well-documented relationship between nitrogen availability and protein synthesis in plants, where increased nitrogen facilitated the formation of amino acids and building blocks of proteins. This finding is particularly important for improving the nutritional quality of wheat. Grain nitrogen uptake more than doubled from 79.57 kg N ha^{-1}at N0 to 165.26 kg N ha^{-1}at N288, while straw nitrogen uptake significantly increased from 39.15 kg N ha^{-1}to 94.00 kg N ha^{-1}. The total nitrogen uptake, including grain and straw, rose dramatically from 118.72 kg N ha^{-1} to 259.14 kg N ha^{-1}, reflecting the enhanced overall nitrogen efficiency at higher fertilization levels. This increased nitrogen uptake supported higher protein content and contributed to greater biomass production, ultimately leading to improved yield. Among the wheat cultivars studied, 'Misr-3' exhibited the highest nitrogen content in both grains and straw and the highest protein content, indicating its strong nitrogen use efficiency. However, 'Sakha-95' excelled in grain and total nitrogen uptake, suggesting its superior ability to convert absorbed nitrogen into productive biomass and protein. On the other hand, 'Giza-171' demonstrated the highest straw nitrogen uptake, highlighting its efficiency in utilizing nitrogen for vegetative growth. These differences among cultivars indicate the importance of selecting the appropriate genotype for specific nitrogen management strategies to optimize nutrient uptake, protein synthesis, and overall crop performance. The highest values for nitrogen content, protein content, and nitrogen uptake in 'Giza-171' and 'Sakha-95' at the highest nitrogen level (288 kg N ha^{-1}) illustrated the variability in genotypic responses to nitrogen availability. These findings are consistent with previous research such as Gawdiya *et al*., (2023) who also reported significant increases in grain protein content and nitrogen uptake with higher nitrogen levels.

The impact of nitrogen on nitrogen use efficiency components is critical in understanding yield improvements. From an agronomic perspective, higher nitrogen use efficiency is a key determinant of crop productivity, as it reflects the plant ability to convert applied nitrogen into harvestable yield. Physiologically, nitrogen affects the root development and nutrient transport systems, improving the plant ability to efficiently absorb and utilize nitrogen from the soil. These factors collectively contribute to the higher yields, emphasizing the importance of effective nitrogen management for enhancing wheat productivity in salt-affected soils. By considering both agronomic and physiological aspects, this study explored how nitrogen influences wheat growth and yield in saline environments. The results indicated significant variations in nitrogen use efficiency components across different N levels and wheat genotypes, displaying the complex dynamics of nitrogen utilization in wheat production. The observed trends in physiological efficiency (PE), agronomic efficiency (AE), agro-physiological efficiency (APE), and apparent recovery efficiency (ARE) underscored the impact of nitrogen management on maximizing crop performance and sustainability. PE, which exhibits the ability of plants to convert absorbed nitrogen into biomass, showed a progressive decline with increasing N levels from 72.04 at N96 to 69.60 at N288. This decrease reflected diminishing returns in biomass production as nitrogen availability increases, where additional nitrogen contributes less to biomass gains due to potential nitrogen saturation. This highlighted the importance of optimizing nitrogen application to avoid excessive use that does not proportionally enhance biomass production. In contrast, AE, APE, and ARE initially increased with nitrogen application, reaching their peak at the moderate nitrogen level of N192 before declining at the highest level of N288. AE increased from 8.78 at N0 to 16.79 at N192, reflecting improved nitrogen conversion into yield at this level, but it decreased to 11.64 at N288, indicating a reduced return on nitrogen at an excessive level. Similarly, APE and ARE followed this trend, with APE peaking at 30.19 and ARE at 55.87% at N192 before declining to 23.91 and 48.75%, respectively, at N288. These results suggest that while moderate nitrogen levels optimize nitrogen use efficiency, excessive nitrogen application may lead to inefficiencies, likely due to nitrogen saturation and reduced uptake efficiency. NUtE and NUE were notably higher at lower nitrogen levels; NUtE decreased from 38.73 at N0 to 30.63 at N288, and NUE declined significantly from 103.33 at N0 to 23.87 at N288. This pattern indicated that wheat plants utilize nitrogen more efficiently at lower levels because the nitrogen available at these levels meets the plant needs without excess. The considerable reduction in efficiency at higher nitrogen levels supports diminishing returns on nitrogen where additional nitrogen inputs do not translate into proportional increases in growth or yield. The observed differences in NUE components among wheat cultivars further emphasized the role of genetic factors in nitrogen use efficiency. 'Misr-3' exhibited the highest PE (72.92), indicating its superior capacity to convert absorbed nitrogen into biomass. In contrast, 'Sakha-95' excelled in AE (14.28) and ARE (53.65%), displaying its effectiveness in converting nitrogen into yield and recovering applied nitrogen. Additionally, the superior performance of

'Sakha-95' in NUtE (36.57) and NUE (53.21) highlights its overall efficiency in utilizing and converting nitrogen into productive biomass, making it a strong candidate for sustainable wheat production. The interaction between nitrogen levels and cultivars significantly impacted all NUE components. The highest PE (75.14) recorded for 'Misr-3' at 288 kg N ha^{-1} and the highest AE (17.97) and ARE (63.59) achieved by 'Sakha-95' at 192 kg N ha^{-1} demonstrated the differential responses of wheat genotypes to nitrogen levels. These results are consistent with previous research on NUE in wheat. Study of Noureldin *et al.*, (2013) reported significant differences in NUE components among wheat genotypes, emphasizing the influence of genetic and environmental factors on nitrogen use. For instance, Noureldin *et al.,* (2013) found substantial differences in AE among wheat cultivars.

Nitrogen stress tolerance among different bread wheat cultivars provided valuable insights into the differential responses of these cultivars to varying nitrogen levels. The significant increases in relative increase in grain yield observed across all three cultivars, 'Giza-171', 'Sakha-95', and 'Misr-3', with increasing nitrogen application, underscore the critical role of nitrogen in enhancing wheat productivity. The progressive yield increase, particularly notable at N192 and N288, highlights the importance of adequate nitrogen fertilization in achieving optimal grain yields. Specifically, 'Sakha-95' demonstrated the highest average relative yield increase (58.9%), followed by 'Giza-171' (52.7%) and 'Misr-3' (51.9%), indicating that while all cultivars benefit from increased nitrogen, 'Sakha-95' is particularly responsive to higher nitrogen levels. However, the analysis of nitrogen stress tolerance measurements, such as the Nitrogen Sensitivity Index, Tolerance Index, and Nitrogen Stress Sensitivity Percentage Index (NSSPI), presented the cultivar performance under nitrogen stress. 'Misr-3' was the most tolerant cultivar to nitrogen deficiency stress, as indicated by consistently favorable scores across all three measurements, particularly at the N96 level compared to N0. 'Giza-171' also showed strong tolerance, although slightly less than 'Misr-3', suggesting that these cultivars are better appropriate for conditions where nitrogen availability may be limited. In contrast, 'Sakha-95', despite its high yield response to increased nitrogen, was identified as the most sensitive cultivar under nitrogen-deficient conditions. This sensitivity suggests that 'Sakha-95' may require more careful nitrogen management to avoid stress-induced yield reductions, particularly when nitrogen application is constrained. 'Misr-3' and 'Giza-171', with their robust tolerance to nitrogen deficiency, may be more reliable choices for environments where nitrogen availability is variable or where lower nitrogen inputs are desired for economic or environmental reasons. On the other hand, 'Sakha-95', while highly productive under optimal nitrogen levels, may require more intensive nitrogen management to achieve its full yield potential, especially in low-nitrogen conditions. These findings are consistent with previous research highlighting the significance of nitrogen stress tolerance measurements in evaluating crop resilience to nutrient stress. Studies by Aga *et al.*, (2021), Ivić *et al.*, (2021), and Awaad *et al.*, (2024) have similarly identified significant differences among wheat genotypes in their tolerance to nitrogen deficiency, emphasizing the value of these measurements in breeding and selection programs aimed at improving nitrogen use efficiency and stress resilience.

The principal component and heatmap analyses are crucial to provide a comprehensive understanding of the complex relationships between treatments and the studied characters (Salem *et al.,* 2020; ElShamey *et al.,* 2022; Omar *et al.,* 2022). PC1 was primarily associated with yield performance across the evaluated treatments. The genotypes S-95-N288 and G1712-288 were situated on the positive side of PC1, showing strong associations with grain yield, biological yield, straw N uptake, spikes m^{-2}, P content in grains, chlorophyll content, K content in straw, and protein content in straw. In contrast, NUE and NUtE were negatively correlated with yield traits, as the highest values for these efficiencies were observed in the low-yielding treatments S95-N0 and G171-N0. PC2 was correlated to canopy temperature depression and plant height. The treatments G171-N96 and S95-N96 were located on the opposite side of PC2, indicating a distinct relationship with these traits. Additionally, a heatmap analysis separated the genotype treatments into distinct clusters. The treatment G171-N288 excelled in traits such as days to heading, N, P, and K contents in grain and straw, grain protein content, grains per spike, 1000-grain weight, grain yield, N uptake, chlorophyll content, flag leaf area, optimal canopy temperature depression, and short plant height. Conversely, the treatments S-95-N0 and M3-N0 were superior in NUtE, NUE, and short plant height, with G171-N0 also excelling in NUtE, NUE, and short plant height. Previous studies have reported significant differences in the behavior of wheat genotypes under varying nitrogen levels, particularly in relation to nutrient uptake and morpho-physiological traits linked to yield (Abd El-Azeiz *et al*., 2021; Aga *et al*., 2021; Ivić *et al*., 2021; Awaad *et al*., 2024). The factor analysis, a powerful tool for detecting fundamental multivariate structures (Walton, 1972), grouped twenty-eight variables into four factors, accounting for 92.47% of the total variability. The results emphasized the importance of phenological and morpho-physiological traits, nutrient components, N uptake, and yield-related traits, particularly those included in Factor 1 in enhancing NUE. These findings align with previous studies by Mam *et al*., (2022), and Awaad *et al*., (2024).

The findings of this study provide valuable insights into nitrogen management strategies for wheat cultivation in saline soils, offering practical implications for farmers seeking to optimize productivity. The results indicated that nitrogen application significantly improves yield and protein content using 288 kg N ha^{-1} being the most effective level for enhancing agronomic traits. However, given the decline in NUE at higher nitrogen rates, farmers should consider a balanced approach that maximizes yield while minimizing excessive nitrogen application. 'Sakha-95' demonstrated superior nitrogen utilization efficiency, this type of genotype is a promising cultivar for regions with saline soils, as it maintains high productivity even under varying nitrogen levels. Farmers cultivating tolerant cultivars like 'Sakha-95' could adopt a split nitrogen application strategy, applying nitrogen in multiple doses throughout the growing season to enhance uptake efficiency and reduce nitrogen loss. Additionally, for cultivars like 'Misr-3', which exhibited greater tolerance to nitrogen deficiency stress, nitrogen rate e.g., 192 kg N ha^{-1} may be more suitable for sustainable production while maintaining adequate grain quality. These findings suggest that site-specific nitrogen management based on soil salinity levels and cultivar selection is crucial for optimizing wheat production under saline conditions.

Conclusions

This study presents the critical role of nitrogen management in influencing the phenological, morpho-physiological, and yield-related characteristics of wheat cultivars in salt-affected soils. This significant interaction effect between nitrogen levels and wheat cultivars, offering valuable insights for optimizing wheat production, especially in salt-affected soils. 'Sakha-95' emerged as the most responsive cultivar, exhibiting superior performance across multiple yield-related traits, including grain yield, straw yield, and nitrogen use efficiency, particularly at higher nitrogen levels. 'Giza-171' also demonstrated strong agronomic potential, especially in terms of 1000-grain weight and nitrogen uptake. 'Misr-3', although less efficient in NUE, excelled in physiological efficiency and demonstrated tolerance to nitrogen deficiency, making it a promising option for conditions where nitrogen supply is limited. The study revealed that proper nitrogen management and cultivars can significantly enhance wheat productivity, especially in saline soils. Farmers in salt-affected regions should consider adjusting nitrogen application rates to optimize yield outcomes while maintaining efficient nitrogen use. However, the study also identified diminishing returns at the highest nitrogen level (288 kg N ha^{-1}), suggesting that excessive nitrogen application may not always be beneficial. Future research should focus on further exploring the underlying mechanisms of nitrogen use efficiency and stress tolerance in wheat cultivars, particularly in saline environments. Additionally, long-term studies assessing the impact of varying nitrogen levels on soil health, nitrogen leaching, and environmental sustainability would be beneficial.

Authors' Contributions

Conceptualization: NHAA, AMH, HAA.; Data curation: NHAA, RHH, KA, ASE, EM; Formal analysis: NHAA, KA, ASE, EM; Funding acquisition: KA, EM; Investigation: NHAA, AMH, ASE, EM, HAA; Methodology: SEF, RHH, KA; Resources: KA, ASE, EM; Software: KA, ASE, EM; Supervision: AMH, SEF, RHH; Validation: AMH, SEF, RHH, KA; Visualization: AMH, SEF, RHH, KA; Writing - original draft: NHAA, KA, EM, HAA; Writing - review and editing: AMH, SEF, RHH All authors read and approved the final manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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