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Effects of water quality and nitrogen on wheat productivity: Experimental and modelling study using the SALTMED model

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Abstract

The effects of different water qualities and nitrogen doses need to be investigated for wheat growth to determine the optimal management strategy for sustaining wheat production potential to ensure human food security. Therefore, a 2-year study (2020–2021 to 2021–2022) was conducted on wheat irrigated with different water qualities, including canal water (Ca), tubewell water (Tu) and mixed Ca-Tu water (Mx), each fertilized with two nitrogen doses, that is, N75 = 75 kgN.ha^{-1} and N100 = 100 kgN.ha^{-1}. Ca×N100 performed best, with 5.12 t.ha^{-1} grain yield, 11.60 t.ha^{-1} biomass, 102.83 cm plant height and 1.32 kg.m^{-3} water productivity. The best values of the root mean square error (RMSE), normalized root mean square error (NRMSE), coefficient of determination (R^2) and coefficient of residual mass (CRM) were 0.11, 0.12, 0.93 and −0.004, respectively, for calibration and 0.13, 0.15, 0.87 and ±0.01, respectively, for validation of the SALTMED model. The scenario simulation was performed for additional levels of water salinity (electrical conductivity [EC] = 8 and 12 dS.m^{-1}) and nitrogen doses (50, 125, 150 and 175 kgN.ha^{-1}). The results revealed improvements in wheat grain yield of 107%, 16% and −6% at EC = 8 dS.m^{-1} and 125%, 31% and 5% at EC = 12 dS.m^{-1}, while the improvements in biomass were 113%, 22% and −2% at EC = 8 dS.m^{-1} and 137%, 29% and 8% at EC = 12 dS.m^{-1} with increasing nitrogen doses from 50–125 kg.ha^{-1}, 125–150 kg.ha^{-1} and 150–175 kg.ha^{-1}, respectively. It is recommended that high-quality water with the lowest possible EC and nitrogen applications of up to 150 kgN.ha^{-1} be adopted for wheat production in semi-arid areas of Punjab, Pakistan.

KEYWORDS

nitrogen doses, SALTMED model, scenario simulation, water salinity, wheat

Article title in French: Effets de la qualité de l'eau et de l'azote sur la productivité du blé: études expérimentales et de modélisation utilisant le modèle SALTMED.

Résumé
Les effets des différentes qualités de l'eau et des doses d'azote doivent être étudiés pour la croissance du blé afin de déterminer la stratégie de gestion optimale pour maintenir le potentiel de production de blé et assurer la sécurité alimentaire humaine. Par conséquent, une étude de deux ans (2020–2021 à 2021–2022) a été menée sur le blé irrigué avec différentes qualités d'eau, y compris l'eau de canal (Ca), l'eau de puits tubulaire (Tu) et l'eau mixte Ca-Tu (Mx), chacune fertilisée avec deux doses d'azote, soit N75 = 75 kgN.ha^{-1} et N100 = 100 kgN.ha^{-1}. Ca×N100 a obtenu les meilleurs résultats, avec un rendement en grains de 5,12 t.ha^{-1}, une biomasse de 11,60 t.ha^{-1}, une hauteur de plant de 102,83 cm et une productivité en eau de 1,32 kg.m^{-3}. Les meilleures valeurs de l'erreur quadratique moyenne (RMSE), de l'erreur quadratique moyenne normalisée (NRMSE), de R^2 et du coefficient de la masse résiduelle (CRM) étaient respectivement de 0,11, 0,12, 0,93 et − 0,004 pour l'étalonnage et de 0,13, 0,15, 0,87 et + 0,01, respectivement, pour la validation du modèle SALTMED. La simulation du scénario a été effectuée pour des niveaux additionnels de salinité de l'eau (EC = 8 et 12 dS.m^{-1}) et des doses d'azote (50, 125, 150 et 175 kgN.ha^{-1}). Les résultats ont révélé des améliorations du rendement en grains de blé de 107%, 16% et 6% à EC = 8 dS.m^{-1} et 125%, 31% et 5% à EC = 12 dS.m^{-1}, tandis que les améliorations de la biomasse étaient de 113%, 22% et − 2% à EC = 8 dS.m^{-1} et 137%, 29% et 8% à EC = 12 dS.m^{-1} avec des doses d'azote croissantes de 50 à 125 kg.ha^{-1}, 125–150 kg.ha^{-1} et 150–175 kg.ha^{-1}, respectivement. Il a été recommandé d'utiliser l'eau de haute qualité avec le plus faible niveau de EC possible et des applications d'azote allant jusqu'à 150 kgN.ha^{-1} pour la production de blé dans les zones semi-arides du Pendjab, au Pakistan.

MOTS CLÉS
Blé, Modèle SALTMED, Salinité de l'eau, Doses d'azote, Simulation de scenarios

1 | INTRODUCTION

Pakistan is an agricultural country, and the agricultural sector contributes 22.7% of its gross domestic product (GDP) (GOV., 2022). Wheat is an important staple crop in Pakistan, with an annual production of 26.3 million metric tons, and Punjab has the highest share of this production (GOV., 2022). The population of Pakistan is increasing, triggering a threat to human food security (WB, 2020). The situation is demanding greater food production with the available resources to ensure the basic food supply to the population (Hayat et al., 2023). In the irrigated areas of Punjab, wheat is grown in the rabi season (October to March), when there is a shortage of canal water (good-quality water); therefore, the use of groundwater is encouraged by farmers to fulfil the crop water demand for wheat production even it has poor qualit (Razzaq et al., 2022). The groundwater in Punjab is mostly saline, especially in regions away from rivers or main canals, where the electrical conductivity (EC) ranges from 2 to 10 dS.m^{-1} (Bhatti et al., 2017).

Saline water applications can reduce crop yields (Tekin, 2013); therefore, groundwater can be applied for irrigation by 'smart techniques' so that the negative impact of saline water can be minimized (Gao et al., 2023). Such techniques include conjunctive water application, in which canal water and groundwater are used alternately for irrigation (Vekariya et al., 2021). However, in the present study, a modified conjunctive technique was used in which the groundwater was applied simultaneously with the canal water. In this way, the quality of groundwater is improved by salt dilution with canal water, which increases the advancement rate of water application and reduces irrigation time and seepage losses.

Along with water application, fertilizer is the second most important crop input that determines the production potential of any crop (Panhwar et al., 2019). Nitrogen is at the top among all nutrients required by wheat for its uninterrupted growth (Spiertz, 2010). Nitrogen supports plant growth and physiological processes by facilitating the development of new cells and tissues at each growth stage (Ahanger et al., 2019). The use of nitrogen fertilizer has been proven to be essential for proper plant growth; therefore, farmers apply nitrogen overdosing to wheat crops for the highest possible yield (Choudhury et al., 2018). However, the overdosing of nitrogen is dangerous because it can delay grain formation and lodging due to excessive vegetative growth. Moreover, the excessive use of nitrogen is a risk to the environment due to its leaching, denitrification and volatilization. Therefore, the judicious use of nitrogen should be ensured (Leghari et al., 2016), and hence the farming conditions of the study area need to be explored. The testing of various management options related to irrigation and fertilizer is not feasible in the field; therefore, a crop model could be adopted to assess crop response under varying levels of water quality and nitrogen doses (Chauhdary et al., 2019, 2020, 2024).

Crop models, such as SALTMED, are adequate for simulating crop growth by considering the input conditions related to water, soil, cultivar, environment and different crop processes (Fghire et al., 2015; Hirich et al., 2016; Pulvento et al., 2015). The versatility of SALTMED lies in its generic nature, which makes it applicable to various irrigation systems, soil types, crops and water qualities. It is not limited to specific conditions, making it adaptable across different scenarios (Ragab, 2010, 2015; Rameshwaran et al., 2015; Afzal et al., 2016). SALTMED has been validated against field experiments in various parts of the world, including Syria, Egypt, Crete, Serbia, Italy and Asian countries. Other models also have their own advantages, but the SALTMED model has been selected due to its simulation capabilities and the need to validate it under the semi-arid conditions of Punjab, Pakistan, as a significant addition to the current knowledge.

SALTMED is a powerful crop simulation model that can handle 20 different fields with different crops and varying input conditions in a single run; hence, it is widely used by researchers to study crop responses under variable crop management and climatic conditions (Ragab, 2020). The SALTMED model is also capable of simulating crop behaviour efficiently in relation to soil and water salinity (Ragab, 2020). Hence, in the present study, SALTMED was selected to simulate wheat growth under different nitrogen doses and irrigation water qualities. The objective of this study was to identify, understand and optimize the impact of different irrigation regimes with varying water qualities and nitrogen levels on wheat growth.

2 | MATERIALS AND METHODS

2.1 | Experimental site and weather conditions

The experiments were conducted at farmer fields in Tehsil Gojra, Toba Tek Singh District (latitude 31°9′ N and longitude 72°41′ E) of Punjab, Pakistan (Figure 1). The temperature of the site varies from 6.1°C in winter to 40.5°C in summer (Pakpedia, 2016), with a mean annual rainfall of 450 mm (WWO, 2024). The climate data for two consecutive wheat seasons required for the model run were acquired from the Pakistan Metrological Department (PMD).

2.2 | Soil and water sampling and analysis

There are two irrigation sources at the experimental site: canal water and tubewell groundwater. Canal water is supplied from the Mungi distributary of the Rakh branch, which originates from the Chenab River. The tubewell was installed in a plot adjacent to the experimental site; the well has a borehole depth of 65 m and discharges 28 $L.s^{-1}$. The experiment included three irrigation treatments, that is, canal water (Ca), tubewell water (Tu) and mixed water from the canal and tubewell (Mx). The water samples for all these treatments were collected in bottles from the field water course to analyse their EC, sodium adsorption ratio (SAR) and residual sodium carbonate (RSC) content. The soil samples were collected from the field at three locations (0.3 m sample depth) to form one composite sample for analysis to determine the soil texture, soil EC and soil fertility in terms of organic matter (OM), nitrogen (N), phosphorous (P) and potassium (K). The soil and water samples were analysed in the laboratories of the Faisalabad Ayub Agriculture Research Stations (AARI, Fsd) to determine the quality parameters of the soil and water. The bulk density was determined in the field using the core method through a core apparatus 5 cm in diameter and 7.5 cm in height (Chauhdary, 2018).

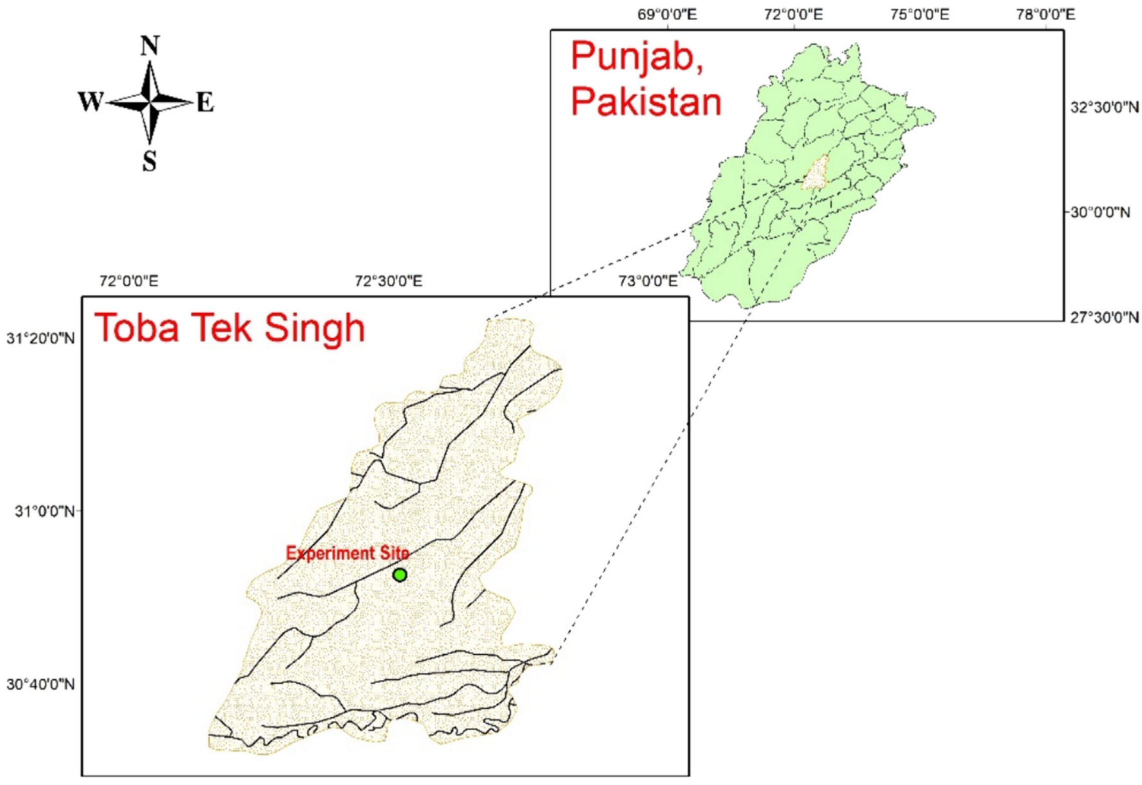

FIGURE 1 Experimental site.

2.3 | Experimental treatments, design and production technology

The experiments were conducted on wheat (Fsd-2008 variety) in two consecutive seasons (2020–2021 and 2021–2022). The wheat was sown on 16 November 2020 and harvested on 6 May 2021 during the 2020–2021 season, whereas it was sown on 21 November 2021 and harvested on 11 May 2022 during the 2021–2022 season. A two-factorial randomized complete block design (RCBD) arrangement was adopted in the field for the application of six treatments, with three replicates for each treatment. The first factor was irrigation water quality, that is, Ca, Tu and Mx, while the second factor was the nitrogen dose (urea fertilizer), with low (N75) and high (N100) nitrogen applications. N75 represents 75 $kgN.ha^{-1}$, and N100 represents 100 $kgN.ha^{-1}$. All the other inputs and management strategies were adopted according to the farming practices of the study area.

2.4 | Data collection and analysis

Soil moisture was measured by a handheld moisture meter (HANNA-MO750) during different stages of the crop growth period (10 times during each season). For crop data, three spots were selected from each replicate of each treatment, and the average value of these spots was considered a single value as recommended by other researchers (Chauhdary et al., 2016; Bakhsh et al., 2018). The samples for data collection regarding crop parameters (grain yield, biomass and plant height) were collected at the time of harvesting. The irrigation data were calculated by multiplying the discharge of the water source by the time of irrigation. Later, the harvest index (HI) and water productivity (WP) were calculated using Equation 1 and Equation 2, respectively. Analysis of variance (ANOVA)-based least significant difference (LSD) tests were used to determine the significance of differences among the results of the different treatments:

$$HI = \frac{\text{Grain yield (kg)}}{\text{Crop biomass (kg)}} \quad (1)$$

$$WP = \left(\frac{kg}{m^3}\right) \frac{\text{Grain yield (kg)}}{\text{Applied water } (m^3)} \quad (2)$$

2.5 | SALTMED applications

The latest version of SALTMED, namely, 3.04.25 (2024) was used in the present study to simulate the effect of different nitrogen doses and irrigation water quality levels.

The model is freely available at the official website of the Water4Crops EU-funded project (http://www.icid.org/res_tools.html#saltmed_2015). The accuracy of model simulations depends on efficient model calibration according to the input conditions of any crop. In the present study, model calibration was performed for wheat irrigated with three water qualities (Ca, Mx and Tu) and fertilized with two nitrogen doses (N75 and N100). The calibration of the model was performed using field data from the 2020–2021 wheat season, followed by its validation using field data from the 2021–2022 wheat season. During calibration, the adjustment of model parameters continued until the acceptable values of selected performance indicators were acquired. After calibration, the model run was performed for validation using the same calibrated model parameters with the measured crop and climatic data from the 2021–2022 cropping years. Calibration and validation were performed for soil moisture, grain yield, biomass and plant height.

The selected performance indicators were coefficient of determination (R^2), root mean square error (RMSE), normalized root mean square error (NRMSE) and coefficient of residual mass (CRM), which are used by many researchers to check the efficiency of model results (Ahmed et al., 2016; Rahman et al., 2018; Chauhdary et al., 2020; Yasin et al., 2022). The R^2 (Equation 3) determines the simulation variation, the RMSE (Equation 4) and NRMSE (Equation 5) determine the error in the simulation, and the CRM (Equation 6) determines under- or overestimation in the simulations:

$$R^2 = \frac{\left[\sum_{i=1}^{n}(O_i - O_{\text{ave}})(P_i - P_{\text{ave}})\right]^2}{\sum_{i=1}^{n}(O_i - O_{\text{ave}})^2 \sum_{i=1}^{n}(P_i - P_{\text{ave}})^2} \tag{3}$$

$$\text{RMSE} = \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}\right]^{0.5} \tag{4}$$

$$\text{NRMSE} = \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}\right]^{0.5} * \frac{1}{(O_{\max} - O_{\min})} \tag{5}$$

$$\text{CRM} = \frac{\sum_{i=1}^{n}O_i - \sum_{i=1}^{n}P_i}{\sum_{i=1}^{n}O_i} \tag{6}$$

In Equations 3–6, n is the number of observations, O_i is the observed value, O_{avg} is the average of all observed values, P_i is the predicted value, and P_{avg} is the average of all predicted values.

After successful calibration and validation, the model was run for additional scenarios of different levels of irrigation water quality and nitrogen doses. The water qualities included the two highest levels of water EC (8 dS.m^{-1} and 12 dS.m^{-1}), and the nitrogen doses included four additional levels (one lower than the experimental treatment and three higher than the experimental treatments), that is, N75 = 75 kgN.ha^{-1}, N125 = 125 kgN.ha^{-1}, N150 = 150 kgN.ha^{-1} and N175 = 175 kgN.ha^{-1}. These scenarios were performed to understand the wheat behaviour against these additional levels.

3 | RESULTS AND ANALYSIS

3.1 | Environment and field conditions of experiment site

The study was conducted at a farmer's field in the Toba Tek Singh District, which is a fertile cultivable area of irrigated agriculture in Punjab, Pakistan. The climate of the study site was moderate during both seasons (2020–2021 and 2021–2022) for wheat growth without any significant environmental disasters. The rainfall was 121 mm in 2020–2021 and 107 mm in 2021–2022. The average solar radiation, maximum temperature and minimum temperature were 15.7 MJ.m^{-2}.day^{-1}, 20.2°C and 8.9°C, respectively, in 2020–2021 and 16.2 MJ.m^{-2}.day^{-1}, 21.2°C and 10.5°C, respectively, in 2021–2022. An illustration of the climatic conditions is shown in Figure 2.

The water quality of the different irrigation sources differed in terms of EC, SAR and RSC. The quality of Ca was good, with the lowest values of EC (0.81 dS.m^{-1}), SAR (8 meq.L^{-1}) and RSC (1.24 meq.L^{-1}), while these values were greater for Mx (EC = 2.18 dS.m^{-1}, SAR = 12 meq.L^{-1} and RSC = 4.12 meq.L^{-1}), indicating the relatively poor quality of Mx compared with that of Ca. However, the quality of Tu was the worst, with an EC of 4.12 dS.m^{-1}, SAR of 16 meq.L^{-1} and RSC of 7.51 meq.L^{-1}. The soil analysis revealed that the soil was sandy clay loam with a bulk density of 1.65 g.cm^{-3}. The quality of the soil was good, with electrical conductivity of soil saturated paste extract ($EC_{e(1:1)}$) = 0.61 dS.m^{-1}, OM = 2.37%, N = 35 ppm, P = 40 ppm and K = 129 ppm. The detailed results of the soil and water analyses are given in Table 1.

3.2 | Effect of treatments

The water quality and nitrogen dose treatments influenced the crop growth and yield parameters. The Ca×N100 treatment had the greatest wheat yield (5.12 T/ha^{-1}), biomass (11.60 T/ha^{-1}), plant height (102.83 cm) and water productivity (1.32 kg.m^{-3}). In comparison to

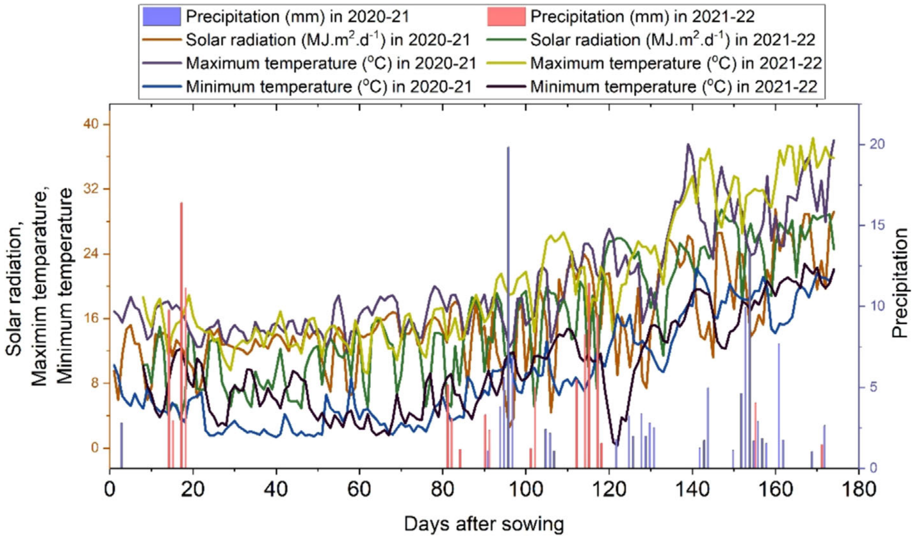

FIGURE 2 Climate conditions of experimental site for both wheat cropping seasons.

TABLE 1 Properties of irrigation water and field soil.

Irrigation water	**ECe (dS.m^{-1})**		**SAR (meq.L^{-1})**		**RSC (meq.L^{-1})**
Ca	0.81		8		1.24
Mx	2.18		12		4.12
Tu	4.12		16		7.51
Soil properties					
Physical properties	**Bulk density (g.cm^{-3})**		**Texture**		
	1.65		Sandy clay loam soil (49.45% sand, 25.25% silt, 25.3% clay)		
Chemical properties	**$EC_{e(1:1)}$ (dS.m^{-1})**	**OM (%)**	**N (ppm)**	**Available P (ppm)**	**Extractable K (ppm)**
	0.61	2.37	35	40	129

Abbreviations: Ca, canal water; EC, electrical conductivity; EC_e, electrical conductivity of soil saturated paste extract; K, potassium; Mx, mixed Ca-Tu water; N, nitrogen; OM, organic matter; P, phosphorous; RSC, residual sodium carbonate; SAR, sodium adsorption ratio; Tu, tubewell water.

the Ca×N100 treatment, yield (5.04 T/ha^{-1}), biomass (11.31 T/ha^{-1}) and water productivity (1.30 kg.m^{-3}) in the Mx×N100 treatment were slightly lower but significantly lower than in the Ca×N100 treatment, while the plant height in the Mx×N100 treatment was significantly lower than that in the Ca×N100 treatment. Tu×N100 significantly increased grain yield (4.63 T/ha^{-1}) but decreased biomass (10.32 T/ha^{-1}), plant height (97.33 cm) and water productivity (1.19 kg.m^{-3}). By exploring the effect of treatments with different water qualities and N75, it was observed that Ca×N75 produced a wheat yield (4.20 T/ha^{-1}) that was significantly lower than that under Ca×N100 (5.12 T/ha^{-1}) and Mx×N100 (5.04 T/ha^{-1}) but significantly the same as that under Mx×N75 (4.12 T/ha^{-1}), Tu×N100 (4.63 T/ha^{-1}) and Tu×N75 (3.75 T/ha^{-1}). The biomass produced by Ca×N75 (9.28 T/ha^{-1}) was significantly lower than that produced by Ca×N100 (11.60 T/ha^{-1}) and Mx×N100 (11.31 T/ha^{-1}) but significantly the same as that produced by Mx×N75 (9.22 T/ha^{-1}) and Tu×N100 (10.32 T/ha^{-1}) and significantly greater than that produced by Tu×N75 (8.50 T/ha^{-1}). The HI was statistically the same for all the treatments. Plant height was statistically the same under Ca×N75 (96.50 cm), Mx×N75 (94.50 cm) and Tu×N100 (97.33 cm), whereas the statistically lowest plant height was produced by Tu×N75 (91.33 cm). Mx×N100 had a significantly shorter plant height (100.50 cm) than Ca×N100 (102.83 cm) but a significantly taller plant height than all the other treatments. Tu×N100 (1.19 kg.m^{-3}) had significantly lower water productivity than Ca×N100 (1.32 kg.m^{-3}) and Mx×N100 (1.30 kg.m^{-3}) but higher water productivity than Ca×N75 (1.08 kg.m^{-3}), Mx×N75 (1.19 kg.m^{-3}) and Tu×N75 (0.96 kg.m^{-3}). Tu×N75 had the lowest water productivity (0.96 kg.m^{-3}). By comparing the wheat behaviour in both cropping seasons, it was revealed that the wheat in the 2020–2021 season performed better than that in the 2021–2022 season. The detailed results regarding the crop parameters are given in Table 2.

3.3 | Model calibration and validation

Model runs were performed for soil moisture and crop parameters (grain yield, biomass and plant height). The first step of model calibration was performed using data from the 2020–2021 season. During calibration, the soil and crop-related model input parameters were fine-tuned to adjust the model predictions to match the observed values. The details of the soil- and crop-related model parameters used in the calibration process are given in Table 3. It is important to mention that only the input parameters taken from the model database or literature were fine-tuned, while the measured input parameters were unchanged.

TABLE 2 Comparison of wheat yield and productivity parameters.

Treatment	Grain yield ($T.ha^{-1}$)	Biomass ($T.ha^{-1}$)	Harvest index	Height (cm)	Water productivity ($kg.m^{-3}$)
Ca×N100	5.12a	11.60a	0.441a	102.83a	1.32a
Ca× N75	4.20bc	9.28cb	0.451a	96.50cd	1.08c
Mx× N100	5.04a	11.31a	0.446a	100.50b	1.30a
Mx× N75	4.12bc	9.22c	0.446a	94.50d	1.06c
Tu× N100	4.63ab	10.32b	0.448a	97.33c	1.19b
Tu× N75	3.75c	8.50d	0.441a	91.33e	0.96d
LSD	0.534	0.394	0.044	2.239	0.029
Comparison by year					
2020–2021	4.87a	10.23a	0.447a	98.67a	1.17a
2021–2022	4.08b	9.84b	0.414b	95.67b	1.14b
LSD	0.030	0.187	0.008	0.558	0.016

Note: Treatment means with different letters are significantly different at $p = 0.05$ according to LSD test.
Abbreviations: Ca, canal water; LSD, least significant difference; Mx, mixed Ca-Tu water; N, nitrogen; Tu, tubewell water.

TABLE 3 Calibrated crop parameters.

Parameter with units	Default value	Calibrated/measured value
Soil parameters		
Saturated water content/porosity (m^3 m^{-3})	–	0.432
Field capacity (m^3 m^{-3})	–	0.22
Wilting point (m^3 m^{-3})	–	0.13
Maximum evaporation depth (mm)	120	88
Lambda pore size distribution index	0.49	0.371
Bubbling pressure (cm)	10	11.25
Saturated hydraulic conductivity (mm/day)	96.9	133
Crop parameters		
Harvest index	–	0.447
Crop coefficient (K_c); initial stage, mid stage, end stage	0.7, 1.15, 1.05	0.6, 1.14, 0.44
Basal or transpiration crop coefficient (K_{cb}); initial stage, mid stage, end stage	0.16, 1.1, 1.0	0.5,0.85,0.45
Leaf area index (LAI); initial stage, mid stage, end stage	1, 8, 7	0.9, 4.2, 4.2
Fraction cover (Fc); initial stage, mid stage, end stage	0.5, 0.85, 1	0.52, 0.94, 0.98
π50 (Osmotic potential at which water uptake reduces to 50%)	5, 5.9, 5.9	8, 10, 12
Plant height (m); initial stage, mid stage, end stage	0.2, 1.0, 1.5	0.4, 0.97, 0.95

After the calibration process, the model was validated using field data from the 2021–2022 season with the same calibrated parameters. The performance of the model run was assessed using the following performance indicators: RMSE, NRMSE, R^2 and CRM. The RMSE values were 0.11, 0.25, 2.19 and 0.83 during calibration and 0.13, 0.54, 1.77 and 1.83 during validation for grain yield, biomass, plant height and soil moisture, respectively. The NRMSE values ranged from 0.11 to 0.19 for calibration and from 0.15 to 0.35 for validation. A comparison between the model-predicted values and observed data revealed better R^2 values, ranging from 0.89 to 0.93 during calibration and 0.84 to 0.88 during validation. An illustration of the data comparison and trendline for R^2 is shown in Figure 3. The highest CRM was −0.02 for biomass during calibration and validation, while the lowest CRM was −0.004 for soil moisture during calibration and ±0.01 for grain yield, plant height and soil moisture during validation. The detailed results regarding these parameters are given in Table 4.

The soil moisture was simulated on a daily basis using SALTMED. The soil moisture was determined in the field at different intervals for comparison with the simulated values. Figure 4 shows illustrations of the simulated versus observed soil moisture with applied irrigation and rainfall.

The SALTMED model was run with hypothetical scenarios depicting additional levels of irrigation water salinity and nitrogen doses. Wheat growth was simulated against four hypothetical levels of nitrogen, namely, 75 kgN.ha^{-1}, 125 kgN.ha^{-1}, 150 kgN.ha^{-1} and 175 kgN.ha^{-1}, to understand crop behaviour as the nitrogen dose increased or decreased. These doses were simulated for two hypothetical levels of water salinity, that is, 8 dS.m^{-1} and 12 dS.m^{-1}. The results revealed that the grain yield increased by 107% (from 1.90 t.ha^{-1} to 3.93 t.ha^{-1}) and 16% (from 3.93 t.ha^{-1} to 4.56 t.ha^{-1}) when the nitrogen dose increased from 50 kg.ha^{-1} to 125 kg.ha^{-1} and from 125 kg.ha^{-1} to 150 kg.ha^{-1}, respectively, while the yield decreased by 6% (from 4.56 t.ha^{-1} to 4.29 t.ha^{-1}) when the nitrogen dose further increased to 175 kg.ha^{-1} against EC = 8 dS.m^{-1}. Similarly, the biomass increased by 113% (from 3.73 t.ha^{-1} to 7.92 t.ha^{-1}) and 22% (from 7.92 t.ha^{-1} to 9.69 t.ha^{-1}) when the nitrogen dose increased from 50 kg.ha^{-1} to 125 kg.ha^{-1} and from 125 kg.ha^{-1} to 150 kg.ha^{-}1, respectively, while it started to decrease by 2% (from 6.69 T.ha^{-1} to 9.52 T.ha^{-1}) when the nitrogen dose further increased to 175 kg.ha^{-1} against EC = 8 dS.m^{-1}. However, for an EC of 12 dS.m^{-1}, the grain yield increased by 125% (from 1.20 t.ha^{-1} to 2.70 t.ha^{-1}), 31% (from 2.70 t.ha^{-1} to 3.53 t.ha^{-1}) and 5% (from 3.53 t.ha^{-1} to 3.69 t.ha^{-1}) when the nitrogen dose increased from 50 kg.ha^{-1} to 125 kg.ha^{-1}, from 125 kg.ha^{-1} to 150 kg.ha^{-1} and from 150 kg.ha^{-1} to 175 kg.ha^{-1}, respectively. Similarly, crop biomass increased by 137% (from 2.31 t.ha^{-1} to 5.47 t.ha^{-1}), 29% (from 5.47 t.ha^{-1} to 7.08 t.ha^{-1}) and 8% (from 7.08 t.ha^{-1} to 7.61 t.ha^{-1}) when the nitrogen dose increased from 50 kg.ha^{-1} to 125 kg.ha^{-1}, from 125 kg.ha^{-1} to 150 kg.ha^{-1} and from 150 kg.ha^{-1} to 175 kg.ha^{-1}, respectively, against EC = 12 dS.m^{-1}. Moreover, the corresponding nitrogen doses under water with an EC of 8 dS.m^{-1} produced 14%–37% more grain yield and 20%–38% more biomass than did

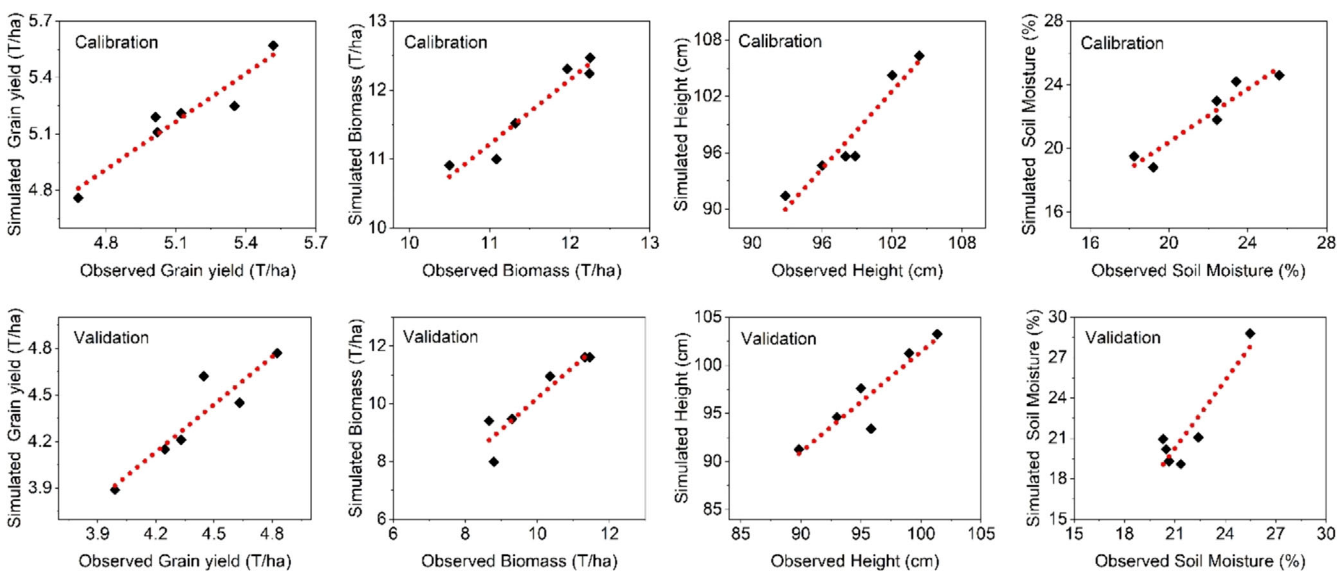

FIGURE 3 Comparison between observed and simulated values of crop and soil parameters during calibration and validation of the SALTMED model.

TABLE 4 Model calibration and validation performance analysis for crop parameters.

Model run	Treatment	Grain yield (T.ha^{-1})		Biomass (T.ha^{-1})		Plant height (cm)		Soil moisture (%)	
		Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
Calibration	Ca×N100	5.52	5.57	11.97	12.31	104.33	106.32	18.3	19.5
	Ca× N75	5.12	5.21	12.25	12.24	98.00	95.65	19.2	18.8
	Mx× N100	5.35	5.25	11.08	11.00	102.00	104.24	25.6	24.6
	Mx× N75	5.01	5.19	12.25	12.47	96.00	94.62	23.4	24.2
	Tu× N100	5.02	5.11	10.50	10.91	98.83	95.63	22.4	23.0
	Tu× N75	4.68	4.76	11.32	11.52	92.83	91.42	22.5	21.8
	RMSE	0.11	–	0.25	–	2.19	–	0.83	–
	NRMSE	0.13	–	0.14	–	0.19	–	0.11	–
	R^2	0.91	–	0.93	–	0.92	–	0.89	–
	CRM	−0.01	–	−0.02	–	0.01	–	−0.004	–
Validation	Ca×N100	4.83	4.77	11.45	11.62	101.3	103.3	20.3	21.0
	Ca× N75	4.45	4.62	9.29	9.48	95.0	96.0	22.4	21.1
	Mx× N100	4.63	4.45	11.32	11.62	99.0	101.3	25.5	28.8
	Mx× N75	4.25	4.15	8.79	7.99	93.0	94.0	20.5	20.2
	Tu× N100	4.33	4.21	10.35	10.95	95.8	93.4	20.7	19.3
	Tu× N75	3.99	3.89	8.66	9.41	89.8	91.3	21.4	19.1
	RMSE	0.13	–	0.54	–	1.77	–	1.83	–
	NRMSE	0.15	–	0.19	–	0.15	–	0.35	–
	R^2	0.86	–	0.87	–	0.88	–	0.84	–
	CRM	0.01	–	−0.02	–	−0.01	–	0.01	–

Abbreviations: Ca, canal water; CRM, coefficient of residual mass; LSD, least significant difference; Mx, mixed Ca-Tu water; N, nitrogen; NRMSE, normalized root mean square error; R^2, coefficient of determination; RMSE, root mean square error; Tu, tubewell water.

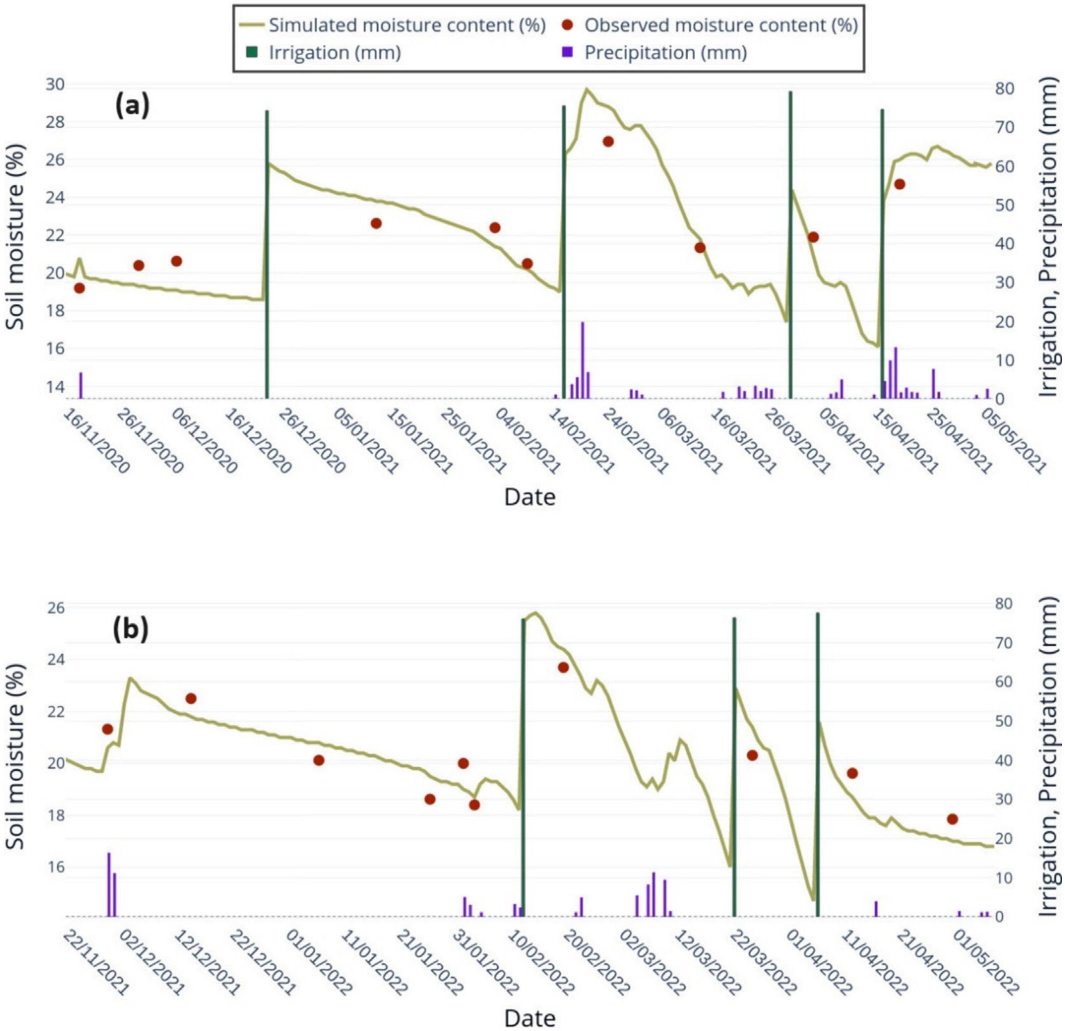

FIGURE 4 Comparison of simulated versus observed soil moisture with irrigation and precipitation during (a) calibration and (b) validation of the SALTMED model.

those under water with an EC of 12 dS.m^{-1}. Wheat grain yield and biomass under the hypothetical scenarios are given in Table 5.

Wheat development under various combinations of hypothetical scenarios involving different nitrogen doses and salinity levels of irrigation water is illustrated in Figure 5. Moreover, the final yield components (grain yield and biomass) and the relative changes in these yield components are also shown at the bottom of Figure 5.

TABLE 5 Wheat grain yield and biomass under hypothetical scenarios.

Hypothetical scenario treatments	Grain yield (T.ha^{-1})	Biomass (T.ha^{-1})
EC = 8 dS.m^{-1} + N50	1.90	3.73
EC = 8 dS.m^{-1} + N125	3.93	7.92
EC = 8 dS.m^{-1} + N150	4.56	9.69
EC = 8 dS.m^{-1} + N175	4.29	9.52
EC = 12 dS.m^{-1} + N50	1.20	2.31
EC = 12 dS.m^{-1} + N125	2.70	5.47
EC = 12 dS.m^{-1} + N150	3.53	7.08
EC = 12 dS.m^{-1} + N175	3.69	7.61

Abbreviation: EC, electrical conductivity.

4 | DISCUSSION

The quality parameters of Ca were identified as best according to irrigation water quality standards in comparison with those of Mx and Tu; however, the quality of Mx was better than that of Tu. According to the literature, irrigation water salinity in terms of EC is considered ideal if it is below 1.5 dS.m^{-1}, while it is considered marginal when it is between 1.5 and 2.7 dS.m^{-1}; however, it is considered poor when it is above 2.7 dS.m^{-1} and is not recommended for the irrigation of crops with low salinity

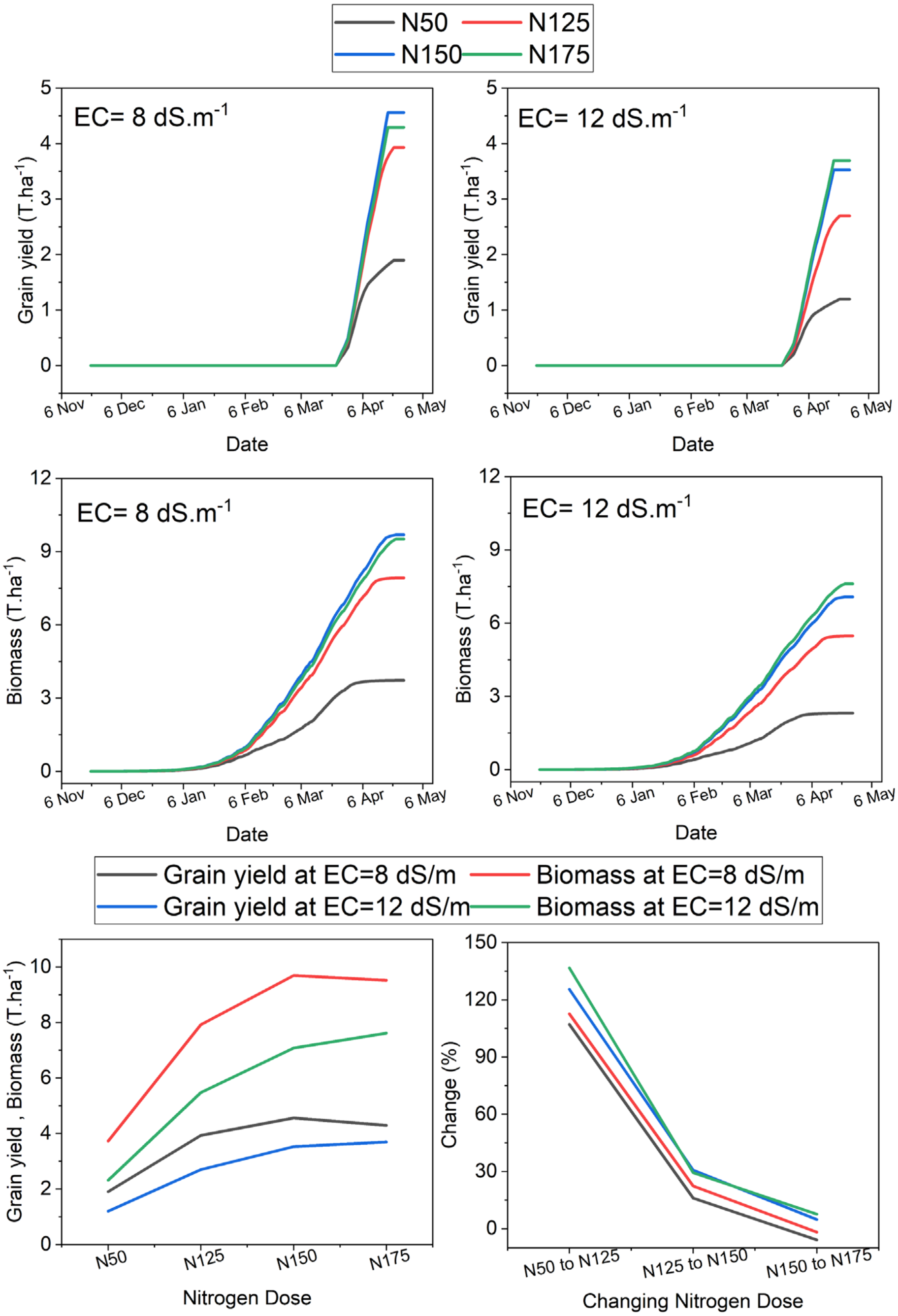

FIGURE 5 Comparative results of crop parameters under different hypothetical scenarios. EC, electrical conductivity.

tolerance (Hashmi et al., 2000; McGeorge, 1954). The value of the SAR is somewhat associated with the EC and is considered safe for irrigation if it is below 10 meq.L^{-1} for Pakistan's conditions (Kinje, 1993). Water with RSC values lower than 1.25 meq.L^{-1} is considered safe for irrigation, while it is marginal up to 2.5 meq.L^{-1} and unsuitable for irrigation beyond RSE = 2.5 meq.L^{-1} (Zaman et al., 2018). The irrigation quality standards were also compiled and reported by Arshad and Shakoor (2017) and are in accordance with the quality standards expressed above.

Wheat yield was affected by the salinity level of the irrigation water. As the salinity of Ca was lowest, the crop responded well to Ca compared to the corresponding nitrogen doses under Mx and Tu. When the quality starts to deteriorate, the wheat yield starts to decrease gradually. The reason behind this yield reduction is the reduction in crop transpiration/water uptake (Rushton et al., 2006). Due to the relatively high salinity in the soil, the net water uptake is reduced at critical crop stages (Er-Raki et al., 2010), when the maximum amount of water is required for grain formation and anthesis (Pakhale et al., 2010). This affects overall wheat growth. Chauhdary et al. (2020) explained another reason for the lower yield under saline water application, which is that saline water increases the salt concentration in the root zone. A relatively high salt concentration restricts moisture movement from the soil to the plant roots due to the relatively high osmotic potential in the root zone, especially at relatively low moisture content. Insufficient water uptake affects plant growth and final grain yield. This phenomenon has also been explained in other studies (Ragab et al., 2005; Ragab, 2015).

The scenario simulation using SALTMED also confirmed that as the salinity of the irrigation water increased, the wheat growth decreased. Similarly, the wheat yield under 8 $dS.m^{-1}$ was lower than that under the experimental treatments with lower EC (Ca = 0.81 $dS.m^{-1}$, Mx = 2.18 $dS.m^{-1}$ and Tu = 4.12 $dS.m^{-1}$), whereas the wheat yield under 12 $dS.m^{-1}$ was lower than that under 8 $dS.m^{-1}$. The effects of salinity on wheat have also been studied by other researchers, who reported the same trend of yield reduction and poor crop growth under the application of saline water (Abedinpour, 2017; Gao et al., 2023).

Nitrogen is considered the most important yield-affecting factor in wheat production (Shi et al., 2023). An optimum nitrogen dose could improve wheat growth and increase grain and biomass yields. One of the potential reasons for the higher yield was that the higher rate of nitrogen produced a greater number of tillers from the main stem that produced more spikes and grain, which ultimately increased the final yield (Ali et al., 2018). Nitrogen improves wheat yield and water productivity by enhancing photosynthesis and supporting the accumulation of carbohydrates in plant biomass (Yu et al., 2022). Many researchers have explored the potential of nitrogen for wheat growth and supported its application as a major component of fertilization (Abebe, 2016; Sharma & Behera, 2016). However, the level of nitrogen should be in accordance with the cultivar and field conditions so that the plant can use nitrogen efficiently to increase its final yield (Wu et al., 2022). It is true that nitrogen is beneficial for crop growth, but a crop can tolerate nitrogen to a certain limit (S. X. Li et al., 2009) above which nitrogen can accumulate in plant cells, causing cell burning due to ammonium toxicity (Britto & Kronzucker, 2002). The scenario simulations showed that the yield components of wheat improved with increasing nitrogen application, but the potential for yield improvement started to decrease with increasing nitrogen application. Ultimately, the yield started to decrease after the application of nitrogen at a rate of 150 $kgn.ha^{-1}$ under an EC of 8 $dS.m^{-1}$. Chauhdary et al. (2020) reported an improvement in crop yield with increasing fertigation levels, but after a certain limit, the yield started to decrease. The same trend of yield reduction has also been observed by other researchers (Chauhdary, 2018; Ju et al., 2009). However, the crop response under different nitrogen doses was different for the treatments with EC = 12 $dS.m^{-1}$. Wheat yield continued to improve by increasing the nitrogen dose to 175 $kgN.ha^{-1}$. This phenomenon occurred because under EC = 12 $dS.m^{-1}$, the crop was under water stress as the higher salt concentration ceased the water movement from the root zone to the plant. Under these stress conditions, plants subjected to more nitrogen responded positively, and plants consumed excess nitrogen to compensate for the water stress. Therefore, the response of crops under EC = 12 $dS.m^{-1}$ was different than that under EC = 8 $dS.m^{-1}$. A researcher reported a better wheat response under higher nitrogen applications under drought-stressed conditions, confirming the above argument (Nawaz et al., 2012). In the field experiment, the yield response of wheat was poorer from 2021–2022 than from 2020–2021. This was probably due to the lower application of irrigation water as four irrigations were applied in 2020–2021, whereas only three irrigations were applied in 2021–2022. The smaller number of irrigations in 2021–2022 was due to the lighter rainfall events during the development stage. Zhen et al. reported that less water application can significantly affect wheat yield (Zeng et al., 2023). Other studies also support this explanation for lower wheat yield (Q. Li et al., 2010; Peña-Gallardo et al., 2019).

5 | CONCLUSIONS

This study was conducted on wheat production with two levels of nitrogen (N75 = 75 $kgN.ha^{-1}$ and N100 = 100 $kgN.ha^{-1}$) and three qualities of irrigation water (Ca [EC = 0.81 $dS.m^{-1}$], Mx [EC = 2.18 $dS.m^{-1}$] and Tu [EC = 4.12 $dS.m^{-1}$]). The highest grain yield, biomass, plant height and water productivity were obtained under Ca×N100, with values of 5.12 $T.ha^{-1}$, 11.60 $T.ha^{-1}$, 102.83 cm and 1.32 $kg.m^{-3}$, respectively. It was concluded that wheat under N100 performed better than under N75 against the corresponding water qualities, whereas Ca performed better regarding wheat growth than did Mx and Tu against the corresponding nitrogen doses. Similarly, compared with Tu, Mx performed better in terms of wheat growth at the corresponding nitrogen doses. SALTMED performed well during calibration and validation, with RMSE values of 0.11, 0.25, 2.19 and 0.83 during calibration and 0.13, 0.54, 1.77 and 1.83 during validation for grain yield, biomass, plant height and soil moisture, respectively. The NRMSE values ranged from 0.11 to 0.19 for calibration and from 0.15 to 0.35 for validation, while the R^2 values ranged from 0.89 to 0.93 during calibration and from 0.84 to 0.88 during validation. The highest variation in the CRM was −0.004 during calibration and ±0.01 during validation. The scenario simulation showed that the wheat yield increased by 107% and 16% when the nitrogen dose increased from 50 $kg.ha^{-1}$ to 125 $kg.ha^{-1}$ and from 125 $kg.ha^{-1}$ to 150 $kg.ha^{-1}$, respectively, while the yield decreased by 6% when the nitrogen dose further increased to 175 $kg.ha^{-1}$ against EC = 8 $dS.m^{-1}$. However, for a water EC of 12 $dS.m^{-1}$, the grain yield increased by 125%, 31% and 5% when the nitrogen dose increased from 50 $kg.ha^{-1}$ to 125 $kg.ha^{-1}$, from 125 $kg.ha^{-1}$ to 150 $kg.ha^{-1}$ and from 150 $kg.ha^{-1}$ to 175 $kg.ha^{-1}$, respectively. Based on the study's findings, it is recommended that for irrigation water with an EC of up to 8 $dS.m^{-1}$, a nitrogen application of 150 $kgN.ha^{-1}$ is optimal. For higher EC levels (up to 12 $dS.m^{-1}$), increasing the nitrogen dose to 175 $kgN.ha^{-1}$ is optimal. Overall, high-quality water with the lowest possible EC and nitrogen applications up to 150 kg N ha^{-1} should be adopted for wheat production in fertile soils of semi-arid areas of Punjab, Pakistan.

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DATA AVAILABILITY STATEMENT

Detailed data are available from the corresponding author and can be provided upon reasonable request. The findings of the study can be cited and used by other researchers by considering ethical rules.

DISCLOSURE STATEMENT

The authors declare no conflicts of interest.

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