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Modeling wheat growth to determine economic feasibility under deficit irrigation and nitrogen management strategies

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ABSTRACT

The sustainability of any agricultural system depends on economical and feasible use of crop inputs to earn the highest net margin. The fertilizers are the essential inputs for crop production, particularly under varying irrigation conditions. To examine these essentials for wheat production, multi-seasonal experiments on varying levels of deficit irrigation and nitrogen applications were conducted for determining their economic feasibility through modeling applications. The experiment involved two irrigation levels [FI=full irrigation (341.6 mm, equivalent to soil-based crop water requirement), DI80 = 80 % of FI (273.3 mm, deficit irrigation)] and two levels of liquid nitrogen fertilizer (LNF) (N:P:K=32:0:0), labelled as LNF100 (434 Lha^{-1}, 100 % of nitrogen dose) and LNF75 (325.5 Lha^{-1}, 75 % of nitrogen dose). The highest grain yield (5.75 $t.ha^{-1}$), dry matter (14.38 $t.ha^{-1}$) and plant height (101.3 cm) were achieved under FI.LNF100. However, this treatment had lower water productivity compared to DI80.LNF100 (1.69 vs. 2.00 kgm^{-3}). The SALTMED model effectively simulated these dynamics, showing high accuracy and reliability during both calibration and validation phases, with low RMSE for grain yield (0.23–0.29 $t.ha^{-1}$), dry matter (0.45–0.93 $t.ha^{-1}$), plant height (1.1–1.89 cm) and soil moisture (0.68–0.75 %). Moreover, the NRMSE varied from 0.11–0.24, R^2 varied from 0.95–0.85, CRM varied from −0.003–0.05. Additional hypothetical scenarios, including reduced irrigation levels (DI60 and DI50) and increased nitrogen doses (up to LNF200) indicated that optimal yields and dry matter were achieved at LNF150–LNF175, beyond which yields declined. These findings highlight the importance of balanced nutrient management under diverse irrigation conditions. Economic analysis of all scenarios revealed FI.LNF150 (full irrigation with 150 % nitrogen dose) as the most profitable strategy, generating the highest net margin (826 US $\$ha^{-1}$) and BCR (1.44), while DI80LNF175 maximized water economic productivity (0.69 $US\$m^{-3}$). Results indicate two viable optimization strategies for semi-arid wheat systems: (1) FI.LNF150 for maximal profitability and (2) DI80.LNF175 for water-limited conditions, with selection dependent on resource prioritization.

1. Introduction

Pakistan's population is over 220 million (GOV, 2020) and growing at an annual rate of around 2 %, making it the world's fifth-most populous country, impacts the country's food demand and future food security (WB, 2020). Agriculture constitutes Pakistan's largest economic sector (GOV., 2022), with irrigated farming dominating production due to the country's location on the Indus River plain (Yang et al., 2016). Wheat is the largest agricultural commodity in Pakistan, achieves an annual production of 26.3 million tons, playing a pivotal role in national food security (GOV., 2022). In the areas of irrigated agriculture, wheat is grown in winter to spring seasons when there is a significant shortage of

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irrigation water to account seasonal crop water requirement (CWR), which varies from 380–560 mm (Ejaz and Ashraf, 2023; GOV., 2022). Water shortages for wheat production in Pakistan can lead to reduced crop yields, impacting food security and increasing dependence on costly imports to meet domestic demand. To overcome the issue of water shortage, water saving practices need to be evaluated in these regions to draw the alternative options for reducing pressure on current water resources while maintaining the target wheat yields (Brauman et al., 2013). Deficit irrigation holds considerable potential for enhancing the sustainability of wheat production, particularly in water scarce regions of Punjab, Pakistan (Du et al., 2010). The deficit irrigation has several benefits including higher water productivity (WP), improve crop quality, reduce disease and save energy (Du et al., 2015). Zhou et al. reported higher water productivity under deficit irrigation combined with mulching (Zhou et al., 2011). In another research, it was claimed that deficit irrigation upto 50 % does not reduce wheat yield significantly in rainfed area (Gholinezhad and Eivazi, 2022). When it comes to semi-arid regions of central Punjab, the potential of deficit irrigation needs to be further explored. Nutrient supply represents the most critical input for crop production after water availability.

The (Xu et al., 2024) identified the water and nitrogen as key growth determinants, where deficit irrigation decreased yield by 15 %, but strategic nitrogen application offset yield by 7–8 %. Beyond nitrogen, macronutrients such as phosphorus and potassium have similarly been shown to significantly enhance both crop yield and growth potential (Gallardo et al., 2021). At the micronutrient level, numerous studies have confirmed their critical role in improving not only yield quantity but also quality parameters (Saquee et al., 2023; Zalacáin et al., 2021). However, (Yan et al., 2020) highlighted a key limitation under deficit irrigation conditions that the uptake of essential nutrients (N:P:K) by plants was restricted, creating compounded stress effects and resulted low yield. This nutrient-water interaction underscores the importance of optimum moisture and balanced fertilization strategies, particularly through carefully formulated chemical fertilizer compounds that can deliver both macro and micronutrients efficiently. Traditionally, in study area, granular fertilizers including Urea, DAP (Diammonium Phosphate) and SOP (Sulphate of potash) are used for wheat production. The efficiency and absorption rate of these granular fertilizers are low compared to liquid fertilizer by which nutrients are immediately available to plant upon their application (Allouzi et al., 2022). By considering these benefits, liquid fertilizer compounds including multicurrent liquid composition named "LFC" and liquid nitrogen named "LNF" have been developed at Water Management Research Centre, University of Agriculture, Faisalabad that contains all necessary nutrients for optimum plant growth. The traditionally used granular fertilizers (Urea, DAP and SOP) has only four nutrients while LFC has thirteen nutrients including micronutrients. However, while liquid fertilizers offer these benefits, it is important to consider factors such as the cost of liquid fertilizer compared to conventional granular fertilizers. Therefore, the applications of liquid fertilizer should be at optimum level for higher wheat production and economic return. To do optimization of any input like fertilizer or irrigation, crop models could effectively be used to develop simulations with multiple input levels without spending the precious resources in field.

Crop models are invaluable tools in agricultural research and management, offering insights into the complex interactions between crops, weather, soil conditions and management practices. They play a crucial role in understanding and predicting crop growth, development and yield under various field scenarios (Chauhdary et al., 2024a, 2019). The SALTMED is an efficient crop model that has proved its significance and efficiency to sustainable agricultural development by providing insights into water and soil management practices that enhance productivity and reduce environmental degradation (J.N. Chauhdary et al., 2020; Hirich et al., 2016; Ragab, 2020). Unlike many other crop models, SALTMED integrates multiple variables, such as salinity, water balance, and nitrogen dynamics, providing a holistic approach to managing diverse field conditions. The SALTMED can simulate crop growth under different irrigation, salinity and soil conditions, offering a versatile tool for optimizing water and nutrient management in agriculture (Ragab, 2015). Limited research work is available specifically addressing the use of the SALTMED model for liquid fertilizers. While some studies exist on fully soluble fertilizer compounds (Chauhdary et al., 2019; Chauhdary et al., 2020), none directly focus on liquid fertilizers. Therefore, this study aims to expand the model's scope by integrating the applications of liquid nitrogen with varying levels of irrigation, which could enhance crop water productivity and nutrient efficiency. The novelty of this work lies in its attempt to incorporate liquid fertilizer management into the SALTMED model, providing a more comprehensive tool for optimizing both water and nitrogen management for wheat. Furthermore, this study is designed to test the hypothesis that the SALTMED model, when properly calibrated for non-saline conditions, can effectively simulate crop performance in non-saline environments, demonstrating its adaptability and robustness across diverse soil and climatic conditions. In this context, the present study was planned to evaluate the impact of deficit irrigation and liquid nitrogen on wheat growth and uses SALTMED model to predict wheat yield under additional hypothetical scenarios, assessing the feasibility and economic return of various combinations of deficit irrigation and liquid fertilization.

2. Material and methods

2.1. Description of experiment site

The field experiments were carried out on farmer field located in Tehsil Gojra, Toba Tek Singh district (geographical coordinates: 31°9'N, 72°41'E), a region well-known for its fertile lands, dedicated to irrigated farming in Punjab, Pakistan. The average annual precipitation of site is 450 mm (WWO, 2024) and the temperature fluctuates between a minimum of 6.11°C during the winter season to a maximum of 40.55°C in the summer (Pakpedia, 2016). The daily climate data for three growing seasons was acquired from Pakistan Meteorological Department (PMD), which included maximum/minimum temperature, precipitation and solar radiation. The experiment site is shown in Fig. 1. The site has two primary sources for irrigation: canal water and groundwater from a tubewell with a 65 m deep borehole and having 28 Ls^{-1} flow rate.

2.2. Fertilizer compounds and their application

The urea, DAP and SOP were applied as conventional fertilizers to supply major nutrients [Nitrogen (N), Phosphorus pentoxide (P_2O_5), Potassium oxide (K_2O) and Sulphate (SO_4)] to wheat. While, the liquid fertilizer composition (LFC) has been designed to supply all necessary macro and micro-nutrients to the wheat for its optimum growth. The LFC contained 4 % N, 32 % P_2O_5, 18.5 % K_2O, 3 % CaO (Calcium oxide), 2 % MgO (Magnesium oxide), 2 % SO_4, along with 6 ppm Zn (Zinc), 2 ppm Cu (Copper), 10 ppm Fe (Ferrous), 2 ppm Mn (Manganese), 2 ppm B (Boron), 2 ppm Cl^- (Chloride), and 0.05 ppm Mo (Molybdenum). To achieve the required nitrogen levels in LFC for the experimental treatments, additional liquid nitrogen was supplemented separately using liquid nitrogen fertilizer named LNF (32–0–0). The quantities of granular fertilizer for the control treatment and liquid fertilizers (LFC and LNF) were calculated based on the recommended nutrient requirements for wheat production, N:P_2O_5:K_2O= 150:90:60 $kgha^{-1}$ by Punjab Agriculture Department (PAD) for the study site (Agrinfobank, 2019).

2.3. Experiment treatments, layout and field applications

The wheat trials were conducted over the period of three consecutive growing seasons i.e. 2019–2020, 2020–2021 and 2021–2022. The wheat was sown on 16–11–2019 and harvested on 05–05–2020 during 2019–2020; sown on 18–11–2020 and harvested on 07–05–2021 during

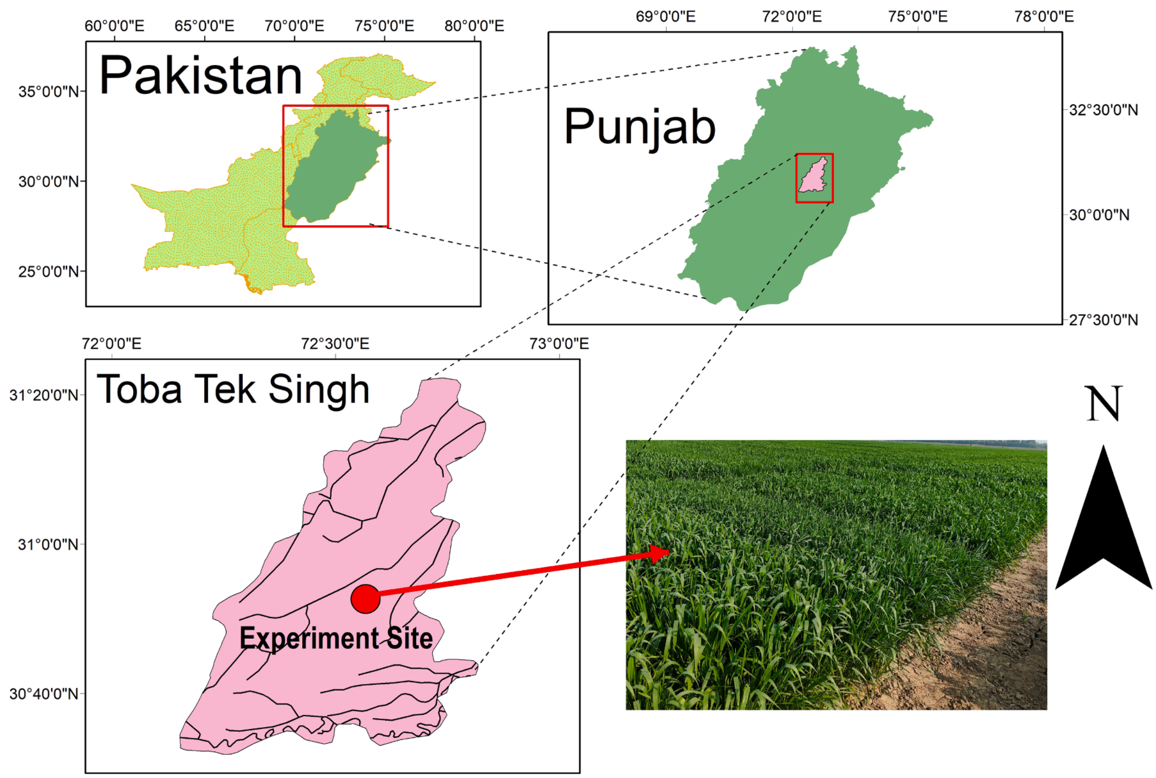

Fig. 1. The Experiment Site and Field Layout.

2020–2021; sown on 21–11–2021 and harvested on 08–05–2022 during 2021–2022. The variety of wheat was Akbar-2019 for all seasons. Akbar-2019 is a high-yielding and rust-resistant wheat variety developed for irrigated regions of Punjab, Pakistan known for its adaptability, resistance to lodging and pests, and biofortification with zinc to improve nutrition and sustainability. The experiment treatments included two levels of liquid nitrogen i.e. (1) LNF100: 434 Lha^{-1} (100 % of recommended dose) and (2) LNF75: 325.5 Lha^{-1} (75 % of recommended dose); and two levels of irrigation i.e. [FI=full irrigation (equivalent to soil-based crop water requirement), DI80 = 80 % of FI (deficit irrigation)]. There was four treatments (1) FI.LNF100 (2) FI.LNF75, (3) DI80.LNF100 and (4) DI80.LNF75. Each treatment has three replicates and those were placed under randomized complete block design (RCBD) arrangement. The layout of experiment is shown in Fig. 1. The surface irrigation (flood irrigation) was used for water applications to wheat. The soil moisture was measured by handheld moisture meter (HANNA-MO750) upto 0.5 m, in each treatment plot right before its irrigation. Then the measured soil moisture was used to determine irrigation depth using Eq. 1 (Bakhsh and Malone, 2017).

$$d_n = \frac{FC - MC}{100} \times As \times r_z \tag{1}$$

Where, FC = soil field capacity, MC = moisture content, A_s =apparent specific gravity of soil, r_z= length of root zone.

Using soil-based calculations for water requirements helps to account the impact of precipitation on crop irrigation needs (Pachang et al., 2024). Upper layer of root zone has been considered for irrigation scheduling by other researchers under farmer field conditions, where the data collection facilities are limited (Chauhdary et al., 2024b). Moreover, crop roots predominantly extract water from the upper soil layers before utilizing moisture from deeper profiles due to the fact that the most plant activities are occurred in the upper root zone (Fan et al., 2016). Also, the moisture in the upper soil layer is lost more rapidly due to the direct exposure to environment, therefore, monitoring soil moisture from upper layer enables timely and responsive irrigation scheduling. This ensures that water is applied before the root zone experiences water stress, optimizing water and crop productivity.

Then, keeping in consideration the area of experimental plot, the irrigation duration was determined by dividing the irrigation depth (measured using Eq. 1) by the discharge rate of the water source and water was then allowed to flow into the plot for that calculated duration. During irrigation, a known and constant discharge rate was maintained through lined watercourse to ensure near to perfect delivery of required irrigation volume in each plot while manual opening/closing mechanism was available at the entrance of each plot to avoid over or under irrigation corresponding to each irrigation treatment (FI or DI80). Although flood irrigation is less effective than pressurized or piped systems in achieving high water uniformity (Ashraf, 2014), however, this method remains the most widely used method in the study area, therefore, experiment treatments reflect real field conditions. To compensate the limitations regarding distribution efficiency associated with flood irrigation, all necessary measures were taken to maximize irrigation efficiency in the field. These measures included designing optimally small sized treatment plots, ensuring precise land leveling and conducting meticulous soil preparation to minimize spatial variability in soil texture and porosity. For the deficit irrigation (DI80 %) treatments, the irrigation time was reduced by 20 % compared to the FI treatment. This reduction in irrigation time directly resulted in 20 % decrease in irrigation volume, ensured the applications of deficit irrigation in field. This control treatment was used as reference to compare the performance of other treatments, having optimized irrigation and liquid nitrogen strategies. The control treatment followed standard farming practices of the region, including full irrigation for the irrigation regime and the application of granular fertilizer compounds consisting of 196 $kgha^{-1}$ of DAP and 249 $kgha^{-1}$ of urea and 120 $kgha^{-1}$ of SOP for the fertilizer levels. In the control treatment, granular fertilizer was applied using the conventional broadcasting method. The DAP and SOP were applied at the time of sowing as basal dose and urea was applied in four splits before each irrigation. On other hand, the liquid fertilizers were applied during irrigation using fertilizer tanks installed at the inlets of each plot to ensure precision and uniformity. The fertilizer solution was continuously injected at the plot inlet throughout the entire irrigation period, ensuring that the full intended quantity of fertilizer was delivered within the calculated irrigation time. The amount of irrigation and fertilizer for each treatment are given in Table 1 and Table 5, respectively.

2.4. Data collection and analysis

Soil samples were taken from multiple locations to a depth of 0.3 m (Chauhdary et al., 2024b) to form composite sample for the purpose of analyzing soil texture, salinity, TDS (total dissolved solids) and fertility expressed by organic matter (OM), nitrogen (N), phosphorus (P), and potassium (K) levels. The fertility of soil was assessed to determine the fertilizer doses, meets the recommendation of PAD. The water salinity from both irrigation sources (canal and tube well) was determined prior to each irrigation. As the mixed water was applied during irrigation (60 % canal and 40 % tube well), therefore, the salinity of mixed water was used in model run. The wheat samples were collected at the time of harvesting. Three sampling areas (one m^2 each) were selected randomly in each plot to measure plant height followed by the wheat harvesting from sampling area for determination of wheat grain yield and dry biomass weight. The wheat harvest index (HI) was calculated by dividing the grain yield by the total dry matter (biomass+grains). Same methodology has been adopted by other researchers (Chauhdary et al., 2024a).

Due to fixed probe length of handheld moisture meter (HANNA-MO750), the moisture was monitored from 0.5 m soil column (maximum capacity of moisture sensor) and monitored soil moisture was used to calibrate and validate the SALTMED model. This approach also referred to applications of SALTMED model using minimum data as stated by other researchers (Chauhdary et al., 2024c, 2019). After successful calibration and validation, the SALTMED was able to simulate the effects of soil moisture dynamics, from deeper layers, on wheat growth, ensuring reliability in the treatment comparisons and outcomes.

The WP is a measure of the efficiency with which water is used in agricultural production. The water productivity (WP) for a particular treatment was calculated by dividing its grain yield with the respective cumulative irrigation volume (Abubaker et al., 2018; Hussain et al., 2021; Mahrous et al., 2022; Rasool et al., 2020, 2019; Tunio et al., 2020).

To determine the feasibility of treatments in monitory terms, net margin (NM), benefit cost ratio (BCR) and water economic productivity (WEP) were calculated. The net margin was calculated by deducting the crop production expenditures from the crop gross margin. The crop production cost included fertilizer cost, crop inputs and labor costs while the crop gross margin denoted the marketable price of wheat produce. The wheat production was calculated according to the methodology, adopted by (Chauhdary et al., 2016). The BCR was calculated using the following equation:

$$BCR = \frac{Crop\ Income(US\$)}{Crop\ Production\ Expenditures(US\$)} \tag{2}$$

The WEP is a key indicator that evaluates the economic return of a crop, generated per unit of water applied for its growth (Cetin and Akinci, 2022). It is calculated using Eq. 3.

$$WEP = \frac{Net\ margin(US\$)}{Irrigation\ applied(m^3)} \tag{3}$$

2.5. SALTMED model applications

The current study utilized the latest version of SALTMED (v. 2015) (Ragab, 2015) to evaluate the impact of varying nitrogen levels (LNF fertilizer) and deficit irrigation. The SALTMED model is a versatile, physically-based tool designed to simulate various processes in the soil-plant-atmosphere system including water movement, nitrogen dynamics, biomass accumulation and crop yield. It uses inputs such as weather data, soil properties, crop characteristics and management practices to model evapotranspiration, soil water redistribution, nitrogen uptake and stress impacts (e.g., salinity or water scarcity). This makes it a comprehensive model for assessing water and nitrogen consumption and predicting crop performance under different scenarios. The model efficiency is well proven to simulate the yield parameters of wheat under erratic input conditions (Ahmed et al., 2016; Soothar et al., 2019), however, the model's precision hinges on its careful calibration tailored to the specific conditions for each crop. In this study, soil moisture, grain yield, biomass and plant height were the selected parameters for calibration and validation during model run. It is worth mentioning that the model was calibrated for the treatments, fertilized with liquid fertilizers (LFC+LNF) with varying level of LNF only while the LFC was same and taken as constant for all treatments.

The model was parameterized using specific inputs including weather, soil, crop and management practices to ensure accurate simulation of the experimental scenarios. Weather data included climatic conditions relevant to the study period. The data such as were incorporated, such as maximum and minimum temperatures, wind speed, solar radiation and rainfall. This data was obtained from the nearest observatory operated by the Pakistan Meteorological Department (PMD). Soil data included saturated water content (porosity, $m^3.m^{-3}$), field capacity ($m^3.m^{-3}$), wilting point ($m^3.m^{-3}$), maximum evaporation depth (mm), saturated hydraulic conductivity ($mm.d^{-1}$), bubbling pressure (cm) and the pore size distribution index (Lambda). Crop data included harvest index, crop coefficient (Kc), leaf area index, fraction cover, and plant height (m). Management practices included details of irrigation (Full Irrigation (FI) and Deficit Irrigation (DI80 %) and nitrogen application. Most of these parameters were measured directly in the field, while others were sourced from the model's database or relevant literature. Furthermore, model run was performed for calibration using two-year wheat data from 2019–2020–2020–2021. During calibration, model parameters were adjusted until achieving

Table 1
Evaluation of treatment effects across experimental conditions.

Treatment	Grain yield ($t.ha^{-1}$)	Dry matter ($t.ha^{-1}$)	Harvest Index HI	Height (cm)	Irrigation (mm)	Water Productivity (kgm^{-3})
FI.LNF100	5.75a ± 0.30	14.38a ± 1.37	0.402abc ± 0.02	101.3a ± 2.92	341.6a ± 33.07	1.69b ± 0.08
FI.LNF75	4.70d ± 0.24	11.42d ± 1.15	0.413ab ± 0.02	95.0c ± 2.74	341.6a ± 31.05	1.38d ± 0.08
DI80.LNF100	5.45b ± 0.36	13.66b ± 1.39	0.401bc ± 0.03	96.5b ± 2.78	273.3b ± 26.46	2.00a ± 0.12
DI80.LNF75	4.35e ± 0.23	10.61e ± 1.29	0.414a ± 0.03	90.5d ± 2.77	273.3b ± 25.80	1.60c ± 0.09
Control	4.84c ± 0.28	12.21c ± 1.25	0.310c ± 0.02	94.5c ± 1.62	341.6a ± 34.72	1.42d ± 0.06
LSD	0.098	0.291	0.0126	0.741	23.088	0.714
Year-wise comparison						
2019–2020	5.13b ± 0.65	12.66b ± 1.75	0.406b ± 0.02	95.40b ± 4.16	322.0b ± 36.56	1.61b ± 0.25
2020–2021	5.24a ± 0.61	13.77a ± 1.67	0.381c ± 0.01	98.37a ± 3.97	345.0a ± 39.17	1.53c ± 0.21
2021–2022	4.68c ± 0.53	10.93c ± 1.54	0.429a ± 0.02	92.93c ± 4.15	276.0c ± 31.33	1.71a ± 0.24
LSD	0.076	0.226	0.010	0.574	17.884	0.055

Treatment means with different letters are significantly different at $P = 0.05$ under LSD (least significant difference) test.

acceptable values for key performance indicators. Following the calibration, a validation run employed the same parameters against the 2021–2022 crop and climatic data. Key performance indicators used included the Coefficient of Determination (R^2) (Chauhdary et al., 2024a, 2024c, 2019; Ragab, 2015), Root Mean Square Error (RMSE) (Chauhdary et al., 2024a, 2024c, 2019), Normalized Root Mean Square Error (NRMSE) (Chauhdary et al., 2024a, 2024c), and Coefficient of Residual Mass (CRM) (Chauhdary et al., 2024a, 2024c, 2019; Ragab, 2015). These indicators are widely used to assess the efficacy of model outputs, as cited by multiple researcher (Chauhdary et al., 2024a, 2024c, 2019). The R^2 quantifies the proportion of variance in the observed data that is captured by the simulation, providing an indication of the model's goodness of fit. RMSE and NRMSE assess the magnitude of the errors between observed and simulated values, offering insights into the overall accuracy and performance of the model. Meanwhile, CRM evaluates the model's bias, indicating whether the simulation tends to systematically underpredict or overpredict the observed values. Together, these metrics provide a comprehensive assessment of the model's performance, capturing both its accuracy and reliability.

The equations for these metrics are:

$$R^2 = \frac{\left[\sum_{i=1}^{n}(O_i - O_{ave})(P_i - P_{ave})\right]^2}{\sum_{i=1}^{n}(O_i - O_{ave})^2 \sum_{i=1}^{n}(P_i - P_{ave})^2} \quad (4)$$

$$RMSE = \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}\right]^{0.5} \quad (5)$$

$$NRMSE = \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}\right]^{0.5} * \frac{1}{(O_{\max} - O_{\min})} \quad (6)$$

$$CRM = \frac{\sum_{i=1}^{n}O_i - \sum_{i=1}^{n}P_i}{\sum_{i=1}^{n}O_i} \quad (7)$$

Where; "*n*" represents the number of observations, "*Oi*" is the observed value, "*Oavg*" is the average of observed values, "*Pi*" is the predicted value, and "*Pavg*" is the average of predicted values.

Following successful calibration and validation, the model was employed to explore additional hypothetical scenarios involving higher levels of deficit irrigation (DI60 = 60 % of full irrigation, DI50 = 50 % of full irrigation) and nitrogen applications LNF75 = 75 % of LNF100, LNF125 = 125 % of LNF100, LNF150 = 150 % of LNF100, LNF175 = 175 % of LNF100 and LNF200 = 200 % of LNF100). The scenario simulations were designed to check the economic return of wheat under extreme conditions regarding irrigation and nitrogen management.

3. Results

3.1. Field conditions and data used for model run

The research was carried out in a farmer's field in three consecutive wheat growing seasons i.e. 2019–2020, 2020–2021 and 2021–2022. The total precipitation, average solar radiation, average maximum and minimum temperature were 118 mm, 15.3 $MJm^{-2}d^{-1}$, 19.4 °C and 8.5 °C, respectively during 2019–2020 season. Similarly, total precipitation, average solar radiation, average maximum and minimum

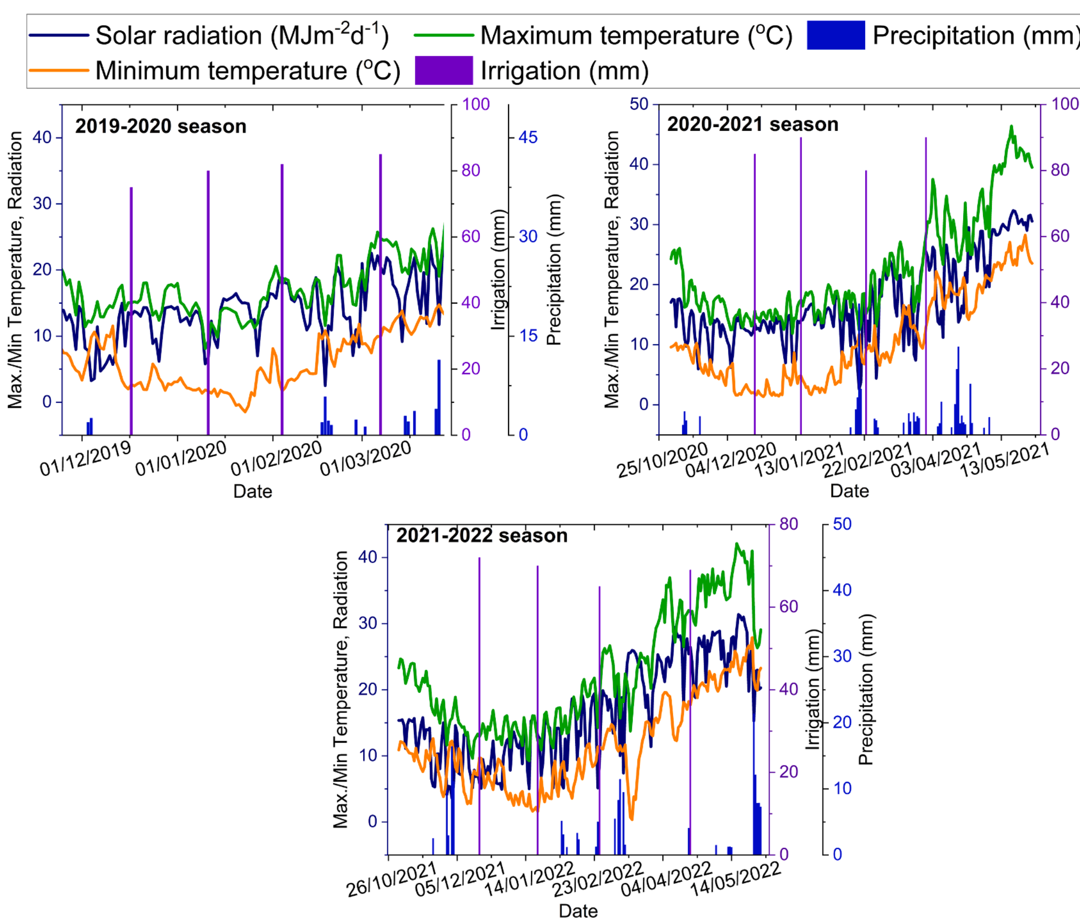

Fig. 2. Weather conditions of the experiment site for three years (2019–2022).

temperature were 122 mm, 15.7 $MJm^{-2}d^{-1}$, 20.2 °C and 8.8 °C, respectively during 2020–2021 season while these were 106 mm, 15.8 $MJm^{-2}d^{-1}$, 20.6 °C and 10.1 °C, respectively during 2021–2022 season. The illustration of climate parameters is given in Fig. 2. Soil of the experiment site was sandy clay loam with 50.32 % sand contents, 23.75 % silt contents and 25.93 clay contents. The bulk density was 1.61 gm^{-3}. The soil has 2.17 % organic matter, 28 ppm nitrogen, 45 ppm available phosphorous and 185 ppm potassium. The amount of organic matter shows that the soil of the experiment plot was fertile. The soil EC_e was 0.432 dSm^{-1}, pH was 7.88, SAR was 4.004 $meqL^{-1}$. The experiment site had two irrigation sources; canal water and tube well water. The EC of canal and tubewell water was 0.31 dS m^{-1} and 1.82 dS m^{-1} , respectively. As irrigation water was a mixture of 60 % canal and 40 % tubewell water, the salinity of the applied water reached 0.914 dS m^{-1} with TDS= 514.96 mgL^{-1}, which is suitable quality for irrigation.

3.2. Response of wheat growth, yield and WP to irrigation and nitrogen treatments

The growth and yield parameters of the wheat were influenced by the treatment involving deficit irrigation and varying levels of liquid nitrogen. The FI.LNF100 produced significantly the highest grain yield (5.75 $t.ha^{-1}$) and dry matter (14.38 $t.ha^{-1}$) followed by the production of these parameters by DI80.LNF100 (5.45 $t.ha^{-1}$ and 13.66 $t.ha^{-1}$, respectively), control (4.84 $t.ha^{-1}$ and 12.21 $t.ha^{-1}$, respectively), FI. LNF75 (4.70 $t.ha^{-1}$ and 11.42 $t.ha^{-1}$, respectively) and DI80.LNF75 (4.35 $t.ha^{-1}$ and 10.61 $t.ha^{-1}$, respectively). The highest HI was produced by DI80.LNF75 (0.414), which was statistically same as produced by FI.LNF75 (0.413) and FI.LNF100 (0.402) and higher than that under FI.LNF100 (0.401), control (0.310). The HI produced by FI.LNF75 (0.413) was same that under DI80.LNF100 (0.401) but higher than control (0.310).

The trend of plant response in terms of its height to different treatments was almost same as observed for grain yield and wheat dry matter. The FI.LNF100 (101.3 cm) produced highest plant height, which was significantly higher than that under DI80.LNF100 (96.5 cm), FI. LNF75 (95.5 cm), control (94.5 cm) and DI80.LNF75 (90.5 cm). The plant height under DI80.LNF100 (96.5 cm) was significantly lower than FI.LNF100 (101.3 cm) but higher than that under all other treatments. It was the same under FI.LNF75 (95.0 cm) and control treatment (94.5 cm) while lowest under DI80.LNF75 (90.5 cm). The irrigation was significantly higher under full irrigation (FI) and control treatments (341.6 mm) compared to deficit irrigation (DI80) treatment (273.3 mm). The irrigation amount was significantly higher (345.0 mm) in 2020–2021 followed by 322.0 mm in 2019–2020 and 276.0 mm in 2021–2022. The significantly highest and lowest WP were achieved under DI80.LNF100 (2.00 kgm^{-3}) and FI.LNF75 (1.38 (kgm^{-3}), respectively.

Overall, it was revealed that the wheat yield and growth parameters under higher nitrogen doses (LNF100) performed better than that under lower doses of LNF (LNF75). On considering the same corresponding nitrogen levels, the WP of fully irrigated (FI) treatments was lower than that under the treatments with deficit irrigation (80 % of FI). Comparing wheat performance regarding its yield across cropping seasons, it was found that wheat performed better in the 2020–2021 season than in the 2019–2020 season followed by 2021–2022 season. Detailed results regarding crop parameters are presented in Table 1.

3.3. Model calibration

In this study, the SALTMED underwent calibration using the data from field regarding experiment treatments and climatic data from 2019–2020 and 2020–2021 seasons. The SALTMED model offers flexibility in calibration, allowing for adjustment of one or multiple parameters. To enhance the accuracy of model validation, we calibrated the model separately for soil and crop parameters. Soil parameters encompassed soil moisture within the crop root zone, while crop parameters included grain yield, dry matter and plant height. The soil and crop related model parameters are interconnected in such a way like the parameters influencing final yield, depended on factors like plant water uptake, which in turn related to soil moisture. Therefore, the adjustment of these parameters was achieved in sequential way to achieve close agreement between observed and simulated datasets during model calibration. The details of these parameters are given in Table 2.

Following the calibration process, the model underwent validation using field and climatic data from the 2021–2022 season, employing the same calibrated parameters (given in Table 2). The accuracy of calibration and validation was examined using performance indicators including RMSE, NRMSE, R^2 and CRM. For grain yield, dry matter, plant height and soil moisture, RMSE values during calibration were 0.23 $t.ha^{-1}$, 0.93 $t.ha^{-1}$, 1.21 cm and 0.68 %, respectively. The NRMSE was 0.15, 0.17, 0.11 and 0.15 for grain yield, dry matter, plant height and soil moisture, respectively. The R^2 and CRM were 0.95 and 0.04, respectively for grain yield; 0.90 and 0.05, respectively for dry matter; 0.93 and 0.001, respectively for plant height; 0.89 and −0.003, respectively for soil moisture. All the performance parameters showed good statistics. The precision of validation is dependent on the accuracy of calibration process. Followed by the accurate calibration, the performance indicators showed good results during validation process. The RMSE, NRMSE and R^2 for grain yield were 0.29 $t.ha^{-1}$, 0.23 and 0.88, respectively; for dry matter were 0.45 $t.ha^{-1}$, 0.15 and 0.88, respectively; for plant height were 1.89 cm, 0.16 and 0.86, respectively and for soil moisture were 0.75 %, 0.24 and 0.85, respectively. It was indicated that model minimally underestimate grain yield, dry matter and soil moisture with the values of CRM as 0.05, 0.01 and 0.023, respectively while it minimally overestimated plant height with CRM= -0.001. Detailed results of model calibration and validation are given in Table 3.

R^2 values ranged from 0.89 to 0.93 during calibration and 0.86–0.89 during validation, indicating a stronger agreement between predicted and observed data during calibration. Fig. 3 illustrates the data comparison and trendline for R^2 during calibration and validation processes.

3.4. Scenario simulations

Following the successful calibration and validation, the model run was performed to draw additional hypothetical scenarios related to the various combinations of additional levels of deficit irrigation (DI60:

Table 2
Calibrated crop parameters.

Parameter with units Crop parameters	Calibrated model parameters
Harvest index (Measured)	0.412
Crop coefficient (Kc) (Literature)	Initial stage:0.65, Mid stage:1.26, End stage:0.48
Basal or transpiration crop coefficient (Kcb) (Literature)	Initial stage:0.5, Mid stage:0.82, End stage:0.43
Leaf area index (LAI) (Literature)	Initial stage:0.95, Mid stage:4.40, End stage:4.21
Fraction cover (Fc) (Literature)	Initial stage:0.54, Mid stage:0.91, End stage:0.87
π50 (Osmotic potential at which water uptake reduces to 50 %) (Literature)	Initial stage:8, Mid stage:11, End stage:11
Plant height (m) (Measured)	Initial stage:0.4, Mid stage:0.94, End stage:0.92
Soil parameters	
Saturated water content/ Porosity (m^3 m^{-3}) (Measured)	0.412
Field capacity (m^3 m^{-3}) (Measured)	0.195
Wilting point (m^3 m^{-3}) (Measured)	0.116
Maximum evaporation depth (mm) (Literature)	95
Lambda pore size distribution index (Literature)	0.367
Bubbling pressure (cm) (Literature)	10.12
Saturated hydraulic conductivity (mmd^{-1}) (Literature)	125

Table 3
Performance analysis of model calibration and validation for crop parameters.

Model run	Year	Treatment	Grain yield ($t.ha^{-1}$)		Dry matter ($t.ha^{-1}$)		Plant height (cm)		Soil moisture (%)	
			Observed	**Simulated**	**Observed**	**Simulated**	**Observed**	**Simulated**	**Observed**	**Simulated**
Calibration	2019–2020	FI.LNF100	5.94	5.71	14.93	14.82	101.0	98.9	23.7	22.9
		FI.LNF75	4.84	4.41	11.89	11.78	94.0	95.2	19.4	20.5
		DI80.LNF100	5.66	5.65	13.41	12.91	97.5	96.0	22.9	22.1
		DI80.LNF75	4.54	4.33	10.58	9.71	91.5	92.7	20.7	20.8
	2020–2021	FI.LNF100	6.11	5.92	15.42	14.11	103.0	102.1	23.3	23.9
		FI.LNF75	5.00	4.85	12.29	10.33	97.0	98.0	19.2	19.3
		DI80.LNF100	5.79	5.50	14.51	13.18	99.50	99.01	25.6	24.8
		DI80.LNF75	4.71	4.30	11.92	11.63	92.50	93.10	20.4	19.7
	—	RMSE	0.23	–	0.93	–	1.21	–	0.68	–
		NRMSE	0.15	–	0.17	–	0.11	–	0.15	–
		R2	0.95	–	0.90	–	0.93	–	0.89	–
		CRM	0.04	–	0.05	–	0.001	–	−0.003	–
Validation	2021–2022	FI.LNF100	5.44	4.98	12.56	12.08	100.0	97.9	22.7	21.8
		FI.LNF75	4.46	4.51	10.16	10.62	93.0	95.0	20.4	19.6
		DI80.LNF100	5.16	4.89	11.74	11.91	94.5	93.1	23.1	22.4
		DI80.LNF75	4.17	3.88	9.55	8.96	88.5	90.5	19.9	20.4
	—	RMSE	0.29	–	0.45	–	1.89	–	0.75	–
		NRMSE	0.23	–	0.15	–	0.16	–	0.24	–
		R2	0.88	–	0.88	–	0.86	–	0.85	–
		CRM	0.05	–	0.01	–	−0.001	–	0.023	–

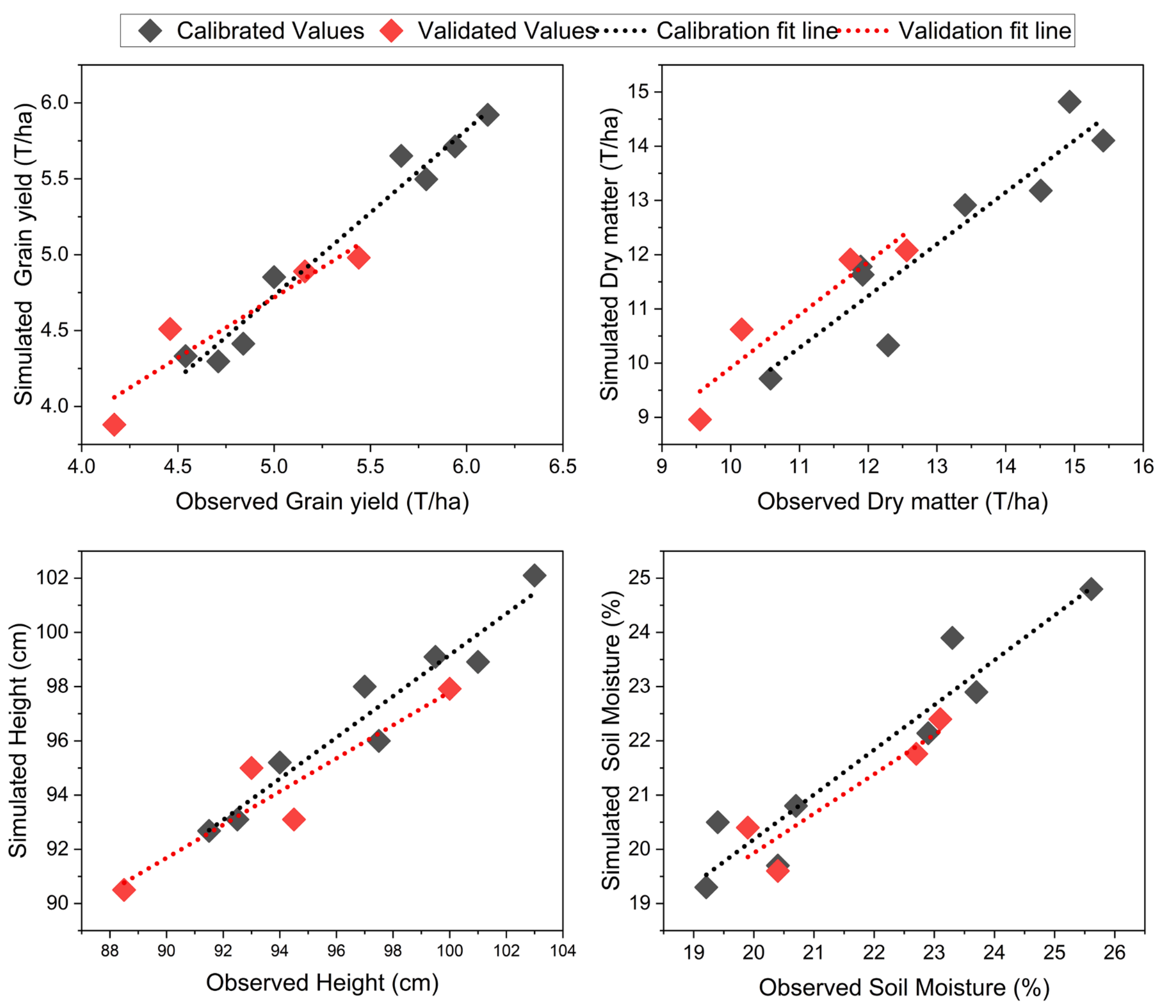

Fig. 3. Comparison between observed and simulated values (a) grain yield during calibration, (b) dry matter during calibration, (c) plant height during calibration, (d) soil moisture during calibration, (a) grain yield during validation, (b) dry matter during validation, (c) plant height during validation and soil moisture during validation.

60 % of FI, DI50: 50 % of FI) and LNF (LNF75: 75 % of LNF100, LNF125: 125 % LNF100, LNF150: 150 % LNF100, LNF175: 175 % LNF100 and LNF200: 200 % LNF100). These hypothetical scenarios were (1) FI. LNF125, (2) FI.LNF150, (3) FI.LNF175, (4) FI.LNF200, (5) DI80. LNF125, (6) DI80.LNF150, (7) DI80.LNF175, (8) DI80.LNF200, (9) DI60.LNF75, (10) DI60.LNF100, (11) DI60.LNF125, (12) DI60.LNF150, (13) DI60.LNF175, (14) DI60.LNF200, (15) DI50.LNF75, (16) DI50. LNF100, (17) DI50.LNF125, (18) DI50.LNF150, (19) DI50.LNF175 and (20) DI50.LNF200.

Within the hypothetical scenarios, the grain yield, dry matter and WP varied across different combinations of irrigation and nitrogen levels. Under full irrigation (FI), the grain yield ranged from 4.69 to 6.84 $t.ha^{-1}$, with the highest yield recorded at FI.LNF175 (6.84 $t.ha^{-1}$), while dry matter ranged from 11.79 to 17.98 $t.ha^{-1}$, also peaking at FI. LNF175 (17.98 $t.ha^{-1}$). The WP under FI ranged between 1.03 and 1.50 kgm^{-3} , with FI.LNF150 achieving the highest value.

Under deficit irrigation at 80 % (DI80), the grain yield increased from 4.35 $t.ha^{-1}$ at DI80.LNF75 to 6.68 $t.ha^{-1}$ at DI80.LNF175, with a slight decline to 6.57 $t.ha^{-1}$ at DI80.LNF200. Similarly, dry matter improved from 10.47 $t.ha^{-1}$ to a maximum of 16.84 $t.ha^{-1}$ at DI80. LNF175, before declining to 16.45 $t.ha^{-1}$. The highest WP was at DI80. LNF175 (1.72 kgm^{-3}) and started to decline towards DI80.LNF200 and reached at 1.69 kgm^{-3}.

For deficit irrigation at 60 % (DI60), the grain yield gradually increased from 2.40 $t.ha^{-1}$ at DI60.LNF75 to a maximum of 3.80 $t.ha^{-1}$ at DI60.LNF175, slightly decreasing to 3.77 $t.ha^{-1}$ at DI60.LNF200. Dry matter followed a similar trend, starting at 5.92 $t.ha^{-1}$ and reaching 9.80 $t.ha^{-1}$ at DI60.LNF175, then dropped slightly to 9.50 $t.ha^{-1}$. The WP increased from 0.75 kgm^{-3} at DI60.LNF75 to 1.19 kgm^{-3} at DI60. LNF175 then decreased to 1.18 at DI60.LNF200.

Under deficit irrigation at 50 % (DI50), the grain yield ranged from 1.89 $t.ha^{-1}$ at DI50.LNF75 to a peak of 3.09 $t.ha^{-1}$ at DI50.LNF175, with a slight reduction to 3.08 $t.ha^{-1}$ at DI50.LNF200. Similarly, dry matter increased from 4.37 $t.ha^{-1}$ at DI50.LNF75 to 7.49 $t.ha^{-1}$ at DI50. LNF175 and 7.33 $t.ha^{-1}$ at DI50.LNF200. The WP under DI50 improved from 0.66 kgm^{-3} at DI50.LNF75 to a maximum of 1.08 kgm^{-3} at DI50. LNF175 and retained its value at DI80.LNF200. The illustration of the wheat yield and WP are given in Fig. 4.

It was identified that the wheat grain yield and WP were enhanced with the increasing levels of nitrogen (LNF fertilizer), but the potential of improvement started to decrease beyond the applications of LNF at 175 $kgha^{-1}$. The grain yield improved by 23 %, 14 %, 4 %, 0.3 % and −3 % under FI; 24 %, 15 %, 6 %, 2 % and −2 % under DI80; 25 %, 16 %, 6 %, 3 % and −1 % under DI60; 26 %, 17 %, 7 %, 4 % and −0.3 % under DI50 when nitrogen level moved from 75 % to 100 %, 100–125 %, 125–150 %, 150–175 % and 175–200 %, respectively. Moreover, the dry matter improved to 25 %, 14 %, 6 %, 1 % and −4 % under FI; 26 %, 15 %, 8 %, 2 % and −2 % under DI80; 26 %, 18 %, 8 %, 3 % and −3 % under DI60; 27 %, 20 %, 10 %, 3 % and −0.1 % under DI50 when nitrogen level moved from 75 % to 100 %, 100–125 %, 125–150 %, 150–175 % and 175–200 %, respectively. Apparently, similarly trend regarding water productivity was observed. The WP

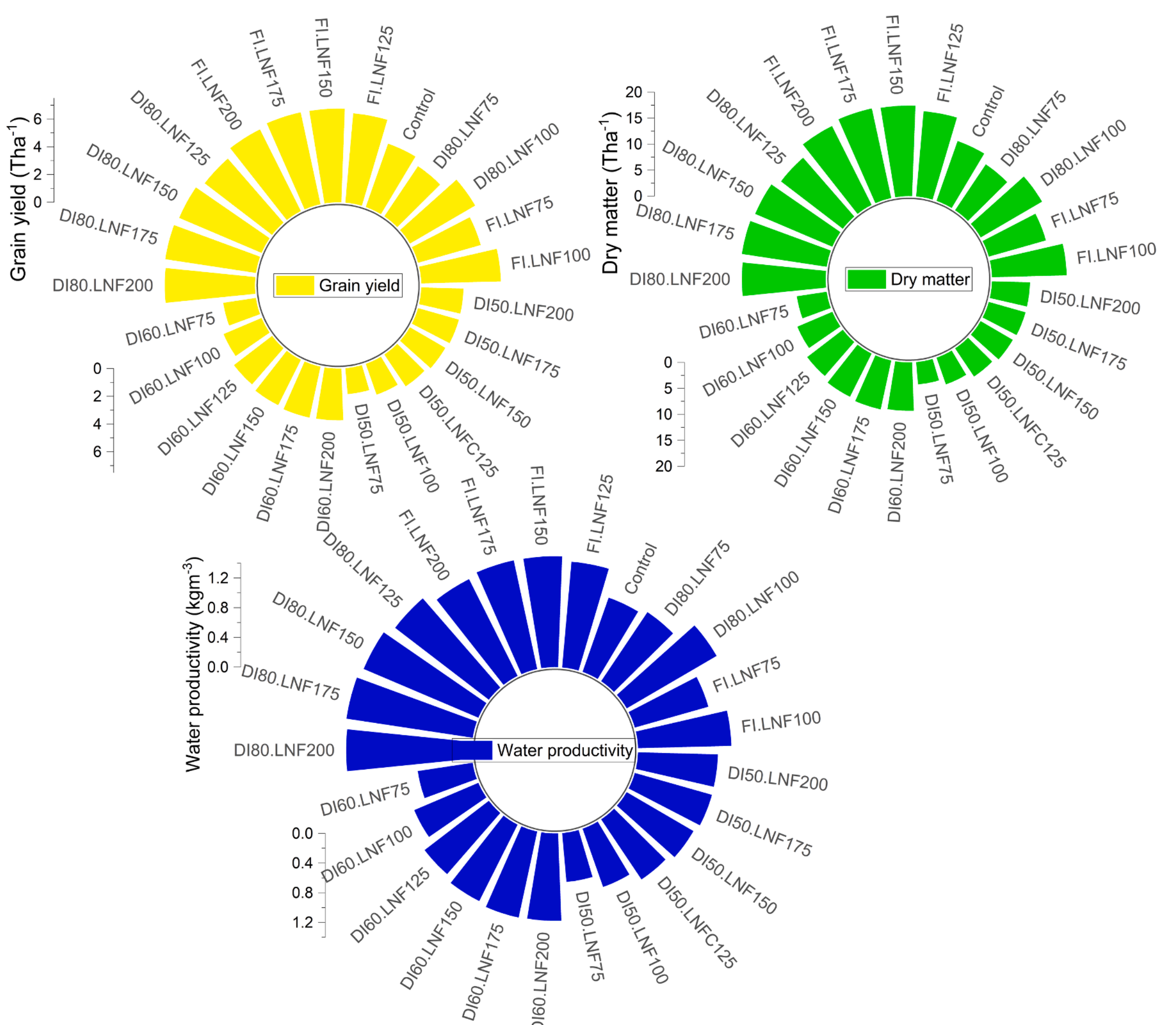

Fig. 4. Wheat grain yield, Dry matter and WP obtained from the hypothetical scenarios versus the experimental values.

improved by 22 %, 14 %, 4 %, 0.3 % and −3 % under FI; 25 %, 13 %, 6 %, 2 % and −2 % under DI80; 25 %, 16 %, 6 %, 3 % and −1 % under DI60; 26 %, 17 %, 7 %, 4 % and 0 % under DI50 when nitrogen level moved from 75 % to 100 %, 100–125 %, 125–150 %, 150–175 % and 175–200 %, respectively. The trend of the behavior of wheat growth parameters and WP were plotted and the best fit lines were drawn to identify the equations regarding each situation. Overall, the average change under all irrigation regimes was 24 %, 15 %, 6 %, 2 % and −1 % for grain yield while 27 %, 18 %, 7 %, 2 % and −3 % for dry matter when nitrogen level moved from 75 % to 100 %, 100–125 %, 125–150 %, 150–175 % and 175–200 %, respectively. The average reduction was 2 %, 46 % and 24 % for grain yield; 14 %, 38 % and 10 % for dry matter when irrigation regime changed from FI to DI80, DI80 to DI60 and DI60 to DI50, respectively. Fig. 5 and Table 4 collectively illustrate the modeled responses of wheat grain yield, dry matter, and water productivity (WP) under varying irrigation regimes and LNF levels. Grain yield and dry matter showed a quadratic response, peaking under full irrigation (FI) and DI80, with coefficients suggesting diminishing returns at higher nitrogen levels. DI80 maintained comparable yield and dry matter to FI, indicating it as an efficient water-saving alternative. In contrast, WP was highest under DI80, as evident from both the figure and the steeper initial slope in its governing equation, suggesting optimal resource use at moderate irrigation.

Table 4
Governing equations for response trends of wheat performance under varying irrigation regimes and LNF levels.

Parameter	Irrigation	Equation
Grain yield	FI (Full irrigation)	$y = -0.1593\ x^2 + 1.4813x + 3.403$
	DI80 (80 % of FI)	$y = -0.1449\ x^2 + 1.4321x + 3.103$
	DI60 (60 % of FI)	$y = -0.083\ x^2 + 0.8477x + 1.6186$
	DI50 (50 % of FI)	$y = -0.0654\ x^2 + 0.6918x + 1.2454$
Dry matter	FI (Full irrigation)	$y = -0.4534\ x^2 + 4.2741x + 7.6272$
	DI80 (80 % of FI)	$y = -0.5129\ x^2 + 4.8677x + 6.1962$
	DI60 (60 % of FI)	$y = -0.2338\ x^2 + 2.353x + 3.6378$
	DI50 (50 % of FI)	$y = -0.1673\ x^2 + 1.7873x + 2.621$
Water Productivity (WP)	FI (Full irrigation)	$y = -0.024759\ x^2 + 0.1563x + 0.8188$
	DI80 (80 % of FI)	$y = -0.0262\ x^2 + 0.1604x + 0.9697$
	DI60 (60 % of FI)	$y = -0.0165\ x^2 + 0.1008x + 0.6014$
	DI50 (50 % of FI)	$y = -0.0139\ x^2 + 0.0812x + 0.5616$

3.5. Economic analysis

To calculate total production cost of wheat, the cost of all inputs was added. The details of the production cost are given in Table 5 as fixed cost, irrigation cost and fertilizer cost. The fixed cost refers to the portion of the total cost that remained constant across all treatments, such as land rent, land preparation, seed and labor for sowing and harvesting. While, the irrigation (Sections F) and fertilizer (G) were treatment-specific and depended on the input levels of irrigation and fertilizer applied under each treatment. Accordingly, the total cost for each treatment was calculated as:

Total Cost = Fixed Cost + Irrigation Cost + Fertilizer Cost

A significant portion of the farmers in Punjab, Pakistan belongs to poor category and grow wheat on rented land; therefore, the land rent

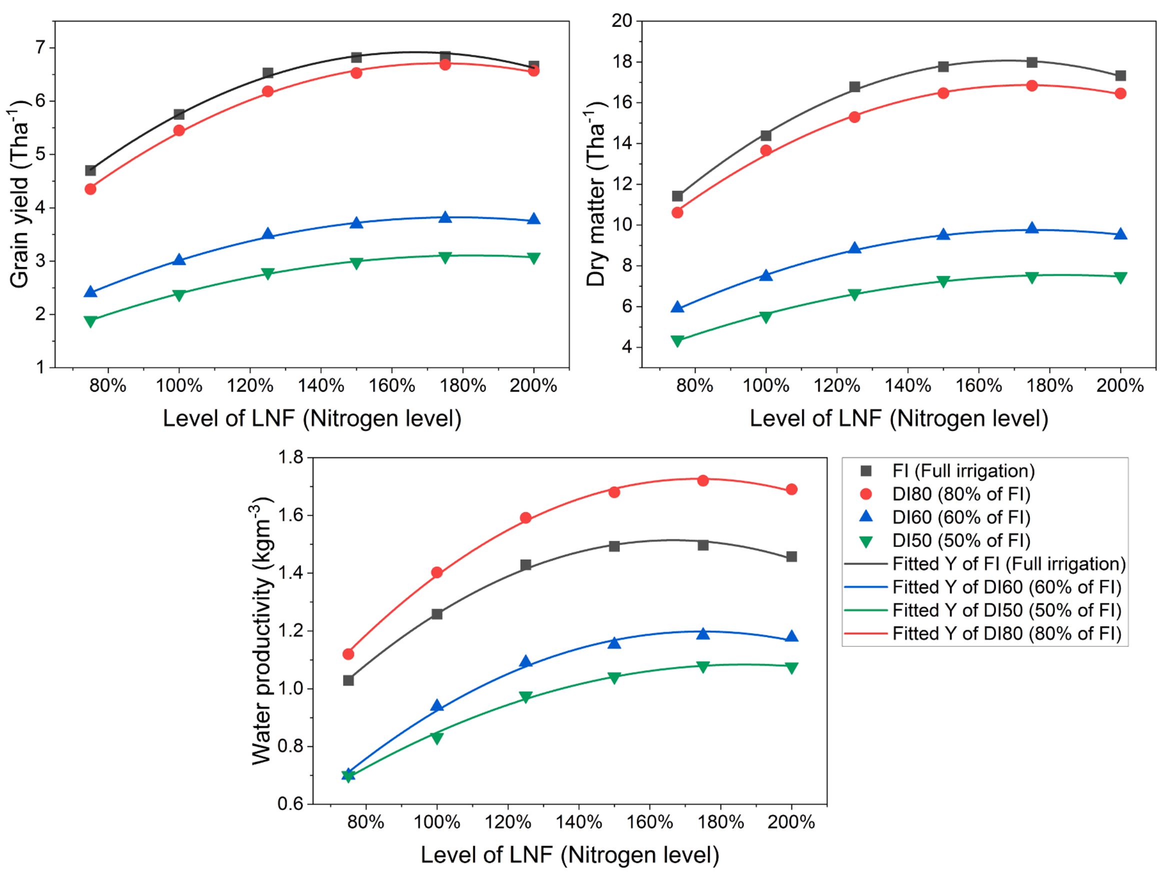

Fig. 5. Simulated wheat grain yield, dry matter, and WP responses to varying irrigation regimes.

Table 5
Cost of wheat production.

Sr. #	Resource/ Crop inputs	Requirement (per hectare)		Unit cost (US$. ha^{-1})	Total cost (US$. ha^{-1})
A	Land rent per hectare	Wheat season (single season)		1000/ season	1000
B	Tillage practices for land preparation	One operation of cultivator + one operation of disk harrow + one operation of planking		70	70
C	Wheat seed	125 kg		0.92 US $.$kg^{-1}$	115
D	Spray	———		55	55
E	Labour for sowign, harvesting and threshing	———		165	165
	Fixed cost* (A+B+C+D+E)				1405
F	Irrigation	Canal/ Tubewell irrigation	FI	40	40
			DDI80	32	32
			DI60	24	24
			DI50	20	20
G	Fertilizer cost	Conventional fertilizer (100 % of P_2O_5:K_2O requirement)	Urea= 249 kg	0.34	88.3
			DAP= 196 kg	0.86	166.8
			SOP= 120 kg	0.83	102.1
					357.2
		LFC	281 L	0.62	174.2
		LNF75	325.5 L	0.42	136.5
		LNF100	434 L	0.42	182.3
		LNF125	542.5 L	0.42	227.9
		LNF150	651 L	0.42	273.4
		LNF175	759.5 L	0.42	318.8
		LNF200	868 L	0.42	364.6

*Fixed cost represents the cost, that is same for all treatments while the costs available in "F" and "G" sections, were according to the input levels corresponding to each treatment.
US Dollar = 282 Pak rupee (04 June 2025)
Per hectare requirement of fertilizer compounds were calculated based on the recommendations of Punjab Agriculture Department which are N: P_2O_5: K_2O= 150:90:60 kg
The unit cost of inputs was taken as average cost of three growing seasons.

was also considered during the calculations of production cost. The tillage operations used reflect standard regional practices, making the production costs generalizable throughout the study area. The cost of wheat seed and sprays (pesticide/insecticides/herbicides) were taken from local market. The As the irrigation was applied from canal water and tubewell water jointly; therefore, the irrigation cost was calculated on the basis of tubewell operating cost-plus fixed charges of canal water which are 4.3 US$ per wheat season in Punjab, Pakistan. The cost of traditional fertilizers (urea, DAP and SOP) was taken from market and the cost of liquid fertilizers were determined by the manufacturer keeping in view the market price of ingredients or chemicals, used for making of LFC and LNF fertilizer.

In case of liquid fertilizer, the fertilizer cost was calculated by adding LFC cost and respective LNF cost.

To determine feasibility of different experiment treatments and hypothetical scenarios regarding possible combinations of different levels of deficit irrigation and fertilization, three critical financial metrics were often analyzed: NM, BCR and WEP (Cetin and Akinci, 2022; Chauhdary et al., 2016). NM, provided a straightforward measure of financial performance for each treatment, whereas the BCR, offered an insight into the efficiency of the investment into each treatment. The WEP served as a key metric to evaluate the financial return per unit of water used, enabling direct comparison of water-use efficiency across deficit irrigation and nitrogen treatments. Among the experiment treatments, FI. LNF100 produced highest net margin (538 US$$ha^{-1}$) with a BCR of 1.30 and EPW of 0.51. This indicates a good economic return under this treatment compared to others. Overall, among hypothetical scenarios, 125–175 % under FI and DI80 (moderate deficit irrigation) showed improved economic gains. While deficit irrigation at 60 % (DI60) and 50 % (DI50) showed reduced yields and poor economic returns with negative net margin. The highest net margin (826 US$$ha^{-1}$) and BCR (1.44) were observed under FI.LNF150 due to higher grain yield, leading to higher gross margin. It shows that despite increased input cost due to higher nitrogen applications, the marginal gross margin exceeded marginal cost, thus maximizing net margin and BCR under FI.LNF150. Highest WEP (0.69) was recorded under DI80.LNF175, describing that moderate deficit irrigation (DI80) conserve water without significantly yield reduction. Overall, the economic analysis highlights that optimal profitability and resource use efficiency in wheat production can be achieved through a strategic balance between irrigation and nutrient inputs. Treatments with moderate water savings (DI80) coupled with enhanced LNF application (175 % of full nitrogen dose) demonstrated the best synergy, achieving high net margins, favorable BCRs and superior water economic productivity. These findings emphasize that maximizing returns does not necessarily depend on maximum input use but rather on the integration of economically and environmentally efficient practices. The detailed calculations regarding these economic indicators are given in Table 6.

Fig. 6 visually compares the economic performance across treatments by plotting net margin, BCR and WEP. The figure highlights that the hypothetical scenarios, especially FI treatments with higher LNF levels (150–175 %) performed best in terms of net margin and BCR while DI80 with higher LNF levels, outperform in terms of WEP while maintaining competitive net margins and BCRs with FI treatments. This reinforces the potential of optimized LNF application under moderate deficit irrigation for balancing profitability and water conservation. Treatments under severe water stress (DI60 and DI50) consistently exhibited negative values for net margin and lower values for BCR and WEP, underlining the economic infeasibility of extreme deficit irrigation strategies.

4. Discussion

During three wheat seasons, it was observed that the yield generally declined from full irrigation (FI) to different levels of deficit irrigation, with a more pronounced drop between DI80 (80 % of full irrigation) to DI60 (60 % of full irrigation). The similar trend of wheat response to different levels of deficit irrigation has also been identified by Thapa (Thapa et al., 2019), who studied the deficit irrigation at 75 % ETc, 65 % ETc and 50 % ETc. A researcher from Iran also reported the reduction in wheat yield and improvement in water productivity under deficit irrigation compared to regular full irrigation (Nasseri and Fallahi, 2007). Li (Li et al., 2019) explained one of the potential reasons for yield reduction that limited moisture under deficit irrigation affects the opening of stomata, reducing the absorption of carbon dioxide and subsequently reducing the photosynthetic activity and lower crop yield. Some researchers determined that the application of deficit irrigation at critical crop stages can affect the wheat yield significantly and recommended to apply deficit irrigation according to crop phenological stages (Li et al., 2010; Peña-Gallardo et al., 2019). Teri (Tari, 2016) found that winter wheat is most sensitive to deficit irrigation during stem elongation and heading stages and reported 55–65 % yield reduction due to limited water application during these stages. Further research by Zhang (Zhang et al., 2022) on winter wheat in the North China Plain demonstrated that applying variable deficit irrigation at different growth stages could save 25–75 % of water without significantly affecting grain yield or total margins. Chowdhury (Chowdhury et al., 2021) emphasized the selection of compatible genotypes under the conditions of deficit irrigation as the response of common genotypes could be severely affected by droughted or water stressed conditions. Similar, approach has also been recommended by Das (Das et al., 2022) to adopt deficit irrigation without compromising the wheat yield. As the regular wheat genotype was used in present study that could be the possible reason for the yield reduction

Table 6
Net margin, BCR and WEP of wheat under experimental treatments and hypothetical scenarios.

	Treatment	Grain yield ($t.ha^{-1}$)	Gross margin* (US$$ha^{-1}$)	Expenditure (US$$ha^{-1}$)	Net margin (US$$ha^{-1}$)	BCR	WEP
Experiment treatment	FI.LNF100	5.75	2339	1802	538	1.30	0.51
	FI.LNF75	4.69	1963	1756	207	1.12	0.43
	DI80.LNF100	5.40	2215	1794	421	1.23	0.57
	DI80.LNF75	4.35	1843	1748	95	1.05	0.47
	Control	4.84	2016	1802	214	1.12	0.44
Hypothetical scenarios	FI.LNF125	6.53	2616	1847	769	1.42	0.57
	FI.LNF150	6.82	2718	1893	826	1.44	0.59
	FI.LNF175	6.84	2726	1938	788	1.41	0.60
	FI.LNF200	6.66	2662	1984	678	1.34	0.58
	DI80.LNF125	6.18	2493	1839	654	1.36	0.64
	DI80.LNF150	6.53	2614	1885	730	1.39	0.67
	DI80.LNF175	6.68	2670	1930	740	1.38	0.69
	DI80.LNF200	6.57	2630	1976	654	1.33	0.68
	DI60.LNF75	2.40	1151	1740	−589	0.66	0.36
	DI60.LNF100	3.01	1366	1786	−420	0.76	0.43
	DI60.LNF125	3.49	1539	1831	−292	0.84	0.48
	DI60.LNF150	3.69	1609	1877	−267	0.86	0.50
	DI60.LNF175	3.80	1646	1922	−276	0.86	0.51
	DI60.LNF200	3.77	1637	1968	−331	0.83	0.51
	DI50.LNF75	1.89	970	1736	−765	0.56	0.34
	DI50.LNF100	2.38	1144	1782	−638	0.64	0.40
	DI50.LNF125	2.79	1289	1827	−538	0.71	0.45
	DI50.LNF150	2.98	1357	1873	−516	0.72	0.47
	DI50.LNF175	3.09	1396	1918	−522	0.73	0.49
	DI50.LNF200	3.08	1392	1964	−572	0.71	0.49

US Dollar = 282 Pak rupee (04 June 2025)
*Gross margin was calculated as 358.9 US$$T^{-1}$ of wheat grains plus 300 US$$ha^{-1}$of wheat dry matter

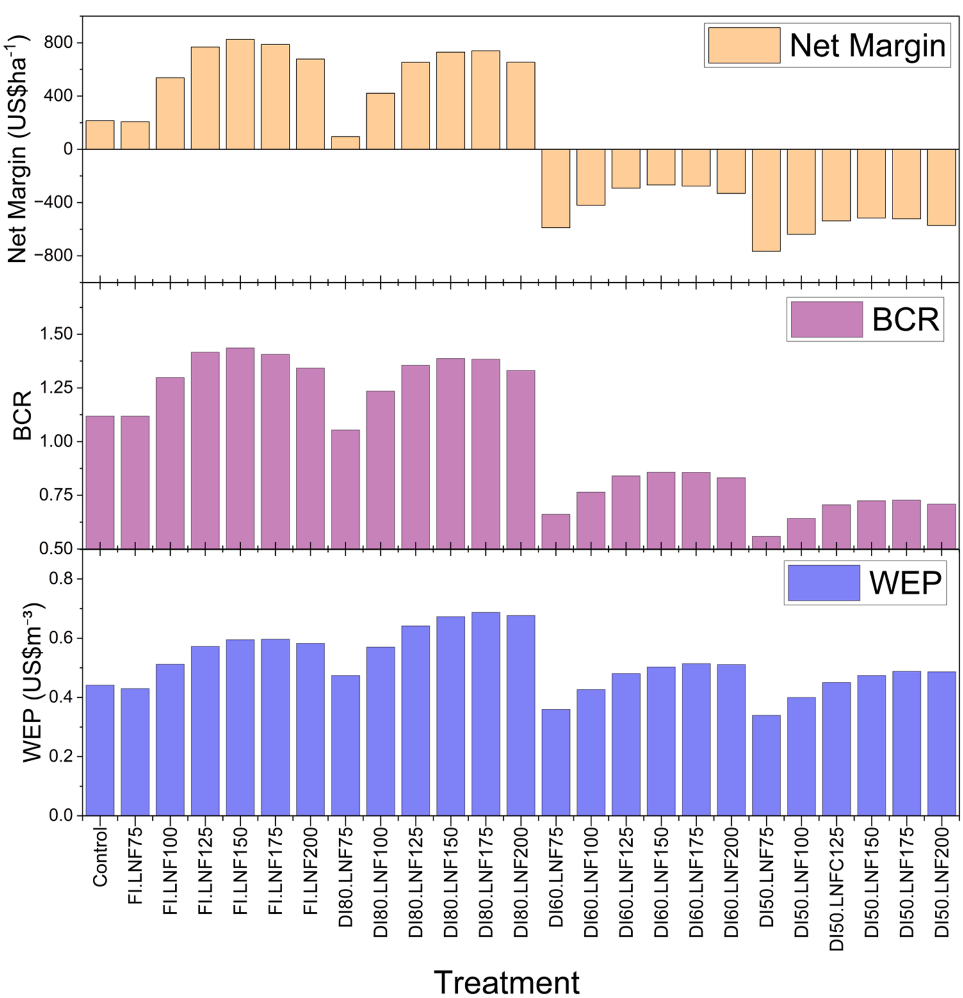

Fig. 6. Illustration of net margin, BCR and WEP against various experiment treatments and hypothetical scenarios.

specially when increasing the level of deficit from DI80 to DI60 and DI50. In current study, the WP of fully irrigated (FI) treatments were lower than that under the treatments with deficit irrigation. Yu (Yu et al., 2020) summarized the results of 41 published papers regarding deficit irrigation through meta-analysis and reported the improvement by 6.6 % in WP under deficit irrigation which are in accordance with the findings of our study.

It was also observed that the wheat response was slightly better towards higher levels of deficit irrigation when nitrogen applications changing from lower to higher doses. It was probably due to the ability of nitrogen to enhance water use efficiency through optimizing water uptake by wheat plants and improve plant physiological characteristics (Ru et al., 2024). This is particularly beneficial in condition where water availability is limited, or deficit irrigation is applied.Top of Form

It was observed that the liquid fertilizers produced more wheat yield than that produced with traditional fertilizers (urea, DAP and SOP). It could have two main reasons. First reason is the presence of micronutrients in liquid fertilizers along with macro nutrients (N-P-K). Second reason for higher wheat yield under liquid fertilizers could be the lower pH of which was around 4.5 (acidic) in comparison to a higher pH (pH=6.7) of traditional fertilizer that helps wheat plant to absorb nutrients efficiently. Chauhdary (Chauhdary et al., 2019) used an acidic fertilizer composition and reported better results regarding crop yield in comparison to alkaline fertilizer composition. (Muhammad et al., 2013) also determined the positive impact of humic acid (acidic fertilizer) for wheat production in Pothowar region of Pakistan.

Simulation of hypothetical scenarios have indicated that yield components of wheat are improved with higher LNF levels, but the potential for yield enhancement diminishes at higher rates. Ultimately, yields begin to decline after nitrogen application exceeds 175 $kgha^{-1}$. Chauhdary (Chauhdary et al., 2019) and Ju et al. (Ju et al., 2009) observed an increase in crop yield with rising fertigation levels, but beyond a certain threshold, yields started to decrease.

Nitrogen plays major role in plant growth and influencing wheat growth yield significantly (Maaz et al., 2021). Numerous researchers have delved into nitrogen's potential for promoting wheat growth, advocating for its application as a primary fertilizer (Abebe, 2016; Sharma and Behera, 2016). Optimized nitrogen levels lead to enhanced wheat growth and increased grain and biomass yield. Ali et al. (Ali et al., 2018) demonstrated the effect of higher nitrogen rates on wheat growth and reported the higher production of main tillers that produced more spikes and grains and final grain yield. Yu et al. (Yu et al., 2022) explained another reason of greater wheat yield under higher nitrogen applications that the nitrogen improves the photosynthesis characteristics of wheat plant and facilitating the accumulation of carbohydrates in plant biomass that produced more yield.

The efficacy of elevated rates of nitrogen application in enhancing wheat production is thoroughly established but uncalculated application of nitrogen can negatively affect the environment (Udvardi et al., 2015); therefore, it is crucial to optimize nitrogen levels according to cultivar and field conditions to ensure efficient nitrogen utilization for optimal yield conversion (Wu et al., 2022). Moreover, there exists a threshold of nitrogen use or absorption by any cultivar, beyond which excessive nitrogen can lead to adverse effects (Li et al., 2009). Du et al. (Du et al., 2021) observed that plants have a tolerance limit for nitrogen, beyond which the nitrogen accumulates in plant cells that can cause ammonium toxicity and result in final yield reduction.

As An interesting phenomenon was observed in which the optimum liquid nitrogen fertilizer (LNF) level for the full irrigation (FI) treatment was 150 %, whereas for the deficit irrigation (DI81) treatment, the optimum level increased to 175 %. This shift may be attributed to the interaction between water availability and nutrient uptake efficiency. Under full irrigation, the soil moisture is adequate, allowing efficient nitrogen uptake at moderate fertilizer levels (150 %), beyond which additional nitrogen may lead to luxury consumption toxicity. In contrast, under deficit irrigation (DI81), water stress can impair root activity and nutrient mobility, potentially limiting nitrogen uptake. As a result, a higher nitrogen supply (175 %) may be required to compensate for reduced efficiency in uptake and to maintain adequate nitrogen availability throughout the crop's growth stages. Additionally, water-limited conditions can slow down mineralization and microbial activity in the soil, further necessitating an increased external nitrogen input to meet crop demands. This response highlights the importance of adjusting nutrient management strategies according to the available moisture conditions in the field.

In the seasonal comparison, it was observed that the wheat yield was poorer in 2021–2022 compared to 2019–2020 and 2020–202, representing the interaction of wheat growth and climate parameters. In 2020–2021 season, despite slightly higher temperatures (20.2°C/8.8°C) and solar radiation (15.7 MJ m^{-2} d^{-1}), achieved the best yields due to optimal water supply (471.7 mm total: 350 mm irrigation + 122 mm precipitation), highlighting water's dominant role. In 2019–2020, moderate temperatures (avg. max/min: 19.4°C/8.5°C) and adequate solar radiation (15.3 MJ m^{-2} d^{-1}) supported wheat productivity when combined with sufficient total water input (493.1 mm irrigation + 118 mm precipitation). However, in 2021–2022, the lowest yields coincided not only with water scarcity (405.9 mm total: 300 mm irrigation + 106 mm precipitation) but also the warmest conditions (20.6°C/10.1°C), which likely exacerbated evapotranspiration losses and heat stress during critical growth stages (Li et al., 2010; Zeng et al., 2023). The consistent correlation between yield and water inputs (Li et al., 2010) was thus modulated by temperature and radiation, with warmer, slightly sunnier years requiring more precise irrigation to offset atmospheric demand (ÇETİN et al., 2022; Peña-Gallardo et al., 2019).

In this study, the SALTMED model was applied to simulate the effects of different irrigation and fertilization levels on wheat growth and yield. The model's ability to simulate soil water dynamics, nutrient uptake and crop performance under varying conditions makes it a valuable tool for assessing the impact of different agronomic practices. Similar applications of the SALTMED model have been reported in previous studies, where it was used to evaluate water use efficiency and optimize irrigation strategies for different crops (Chauhdary et al., 2024c, 2019; Ragab, 2020). These studies, like ours demonstrated the model's effectiveness in predicting crop responses to varying environmental conditions, highlighting its utility in both scientific research and practical farm management.

The economic analysis of wheat cultivation treatments, considering varying irrigation and fertilization conditions, provided valuable insights into their financial feasibility. The total production cost was calculated by including all relevant inputs, such as land rent, tillage operations, seed, pesticide, and irrigation costs (from tubewell and canal water), using local market prices. The cost of traditional fertilizers was sourced from the market, while the cost of LNF fertilizer was based on the manufacturer's pricing. NM, BCR and WEP were used as key metrics to evaluate the economic performance of the treatments. These findings are consistent with similar studies, which highlight the value of optimizing irrigation and fertilization practices for improving both yield and financial outcomes (Chauhdary et al., 2017, 2016; Chauhdary et al., 2020). These results suggest that either FI.LNF150 (highest economic margin and BCR) or DI80.LNF175 (for water-limited conditions) could serve as cost-effective strategies for wheat production in semi-arid regions, depending on resource availability priorities. The economic analysis conducted in this study serves as a crucial tool for guiding agricultural decision-makers in Punjab, helping them make informed choices regarding resource allocation and treatment combinations that optimize both agricultural productivity and profitability.

5. Conclusions

This research evaluated the impact of varying fertilizer levels through the use of an indigenously manufactured liquid fertilizer (LNF) and different levels of deficit irrigation on wheat cultivation. The results demonstrated that the highest grain yield, dry matter and plant height were achieved under the full irrigation and 100 % fertilizer dose treatment (FI.LNF100). However, WP was higher under deficit irrigation treatments (DI80.LNF100). Overall, the application of higher fertilizer levels (LNF100) resulted in better wheat yield and growth parameters compared to lower fertilizer doses (LNF75). Deficit irrigation treatments consistently showed higher WP compared to fully irrigated treatments.

The SALTMED model performed well in simulating these dynamics, with minimal errors in both calibration and validation phases, reflecting high reliability and strong predictive capability. The RMSE for grain yield (0.23–0.29 $t.ha^{-1}$), dry matter (0.45–0.93 $t.ha^{-1}$), plant height (1.1–1.89 cm) and soil moisture (0.68–0.75) was less during calibration and validation processes. Moreover, the NRMSE varied from 0.11–0.24, R2 varied from 0.85–0.95, CRM varied from −0.003–0.05. Further simulations of hypothetical scenarios, incorporating additional fertilizer and irrigation levels, revealed that increasing fertilizer up to 150–175 kgha-1 improved both yield and dry matter, while any further increase led to a decline in crop performance, underlining the importance of balanced nutrient management. Additionally, the reduction in irrigation levels beyond DI80, led to a significant decrease in grain yield, dry matter and WP, emphasizing the critical role of irrigation management in optimizing wheat production. The economic analysis indicated that FI.LNF150 produced highest net margin (826 $US\$ha^{-1}$) and BCR (1.44), while DI80.LNF175 produced highest WEP (0.69 $US\$m^{-3}$). Results indicate two viable optimization strategies for semi-arid wheat systems: (1) FI.LNF150 for maximal profitability and BCR and (2) DI80.LNF175 for water-limited conditions. These findings highlight the potential for optimizing wheat cultivation practices by balancing irrigation and fertilizer application, providing valuable insights for both scientific research and practical farm management decisions.

CRediT authorship contribution statement

Hong Li: Writing – review & editing, Supervision, Conceptualization. **Junaid Nawaz Chauhdary:** Writing – original draft, Validation, Software, Formal analysis, Conceptualization. **Shakeel Ahmad Anjum:** Writing – review & editing, Methodology. **Zawar Hussain:** Visualization, Validation. **Mustafoyev Komil llxomovich:** Writing – review & editing, Validation. **Ragab Ragab:** Writing – review & editing, Software, Formal analysis.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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