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Research Article

Calibration and Evaluation of CERES Model for Durum Wheat (*Triticum turgidum* L.) under Irrigation Managements

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Abstract: *Calibration and Evaluation of crop model is the first step to use appropriate crop model simulation for researchers to forecast how various factors such as weather, soil and agronomic management practices can affect the crop growth and yield performances. The present study aimed to calibrate and evaluate the CERES model for predicting growth and yield of wheat under nitrogen rates and irrigation intervals in central Ethiopia. The treatments of the experiment were included five nitrogen fertilizer rates (0 kg ha^{-1}, 46 kg ha^{-1}, 92 kg ha^{-1}, 138 kg ha^{-1}, and 184 kg ha^{-1}), three irrigation intervals (I_1: application of irrigation water every seven days, I_2: every ten days, and I_3: every thirteen days), and one durum wheat cultivar "Utuba". The experiments were conducted during the 2021/22, 2022/23, and 2023/24 cropping seasons at Debre Zeit Agricultural Research Center (DZARC) in central Ethiopia. The calibration of the CERES model used one year of field data collected during the 2021/22 cropping season. The data used for model evaluation were collected from two years of field experiments conducted during the 2022/23 and 2023/24 cropping seasons. The result of study indicated that the calibrated genetic coefficient of the Utuba cultivar were 10, 20, 380, 11, 79, 0.8, 80 for P1V, P1D, P5, G1, G2, G3 and PHINT, respectively. On the other hand, the model evaluation showed that the strong agreement between the simulated and observed Utuba grain yields, with the percent normalized root-mean-square error (NRMSE %) values ranging from 2.89% to 6.14%, 2.26% to 14%, and 11.6% to 23.01% under seven days(I_1), ten days(I_2), and thirteen days(I_3) irrigation intervals during 2022/23 cropping season and 3.09% to 8.89%, 5.85% to 8.57%, and 7.20% to 22.5% under seven days(I_1), ten days(I_2), and thirteen days(I_3) the respective irrigation water applications during 2023/24 cropping season. Additionally, the error differences (ED) and index of agreement (d-stat) further supported the model's performance. Overall, the evaluation of CERES model demonstrated good accuracy in simulating the growth and yield of the Utuba cultivar in central Ethiopia, highlighting its potential for studying the impacts of various management practices and climate change scenarios.*

Keywords: *Calibration, DSSAT-model, Irrigation, Nitrogen, Model-performance.*

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1. Introduction

Agriculture is crucial to Ethiopia's economy (Urugo, *et al.*, 2024), accounting for 50% of the gross domestic product (GDP), generating 80% of exports, and employing around 75% of the population (Yigezu, 2021; Zerssa *et al.*, 2021; Mohammed, 2022). However, the sector faces several challenges that threaten food security and self-sufficiency, including poor agronomic practices such as ineffective soil nutrient management, inadequate weed control, and insufficient crop protection strategies (Ado and Abubakar, 2024; Mihrete and Mihretu, 2025). Additionally, climate variability, particularly erratic rainfall, worsens agricultural difficulties (Gebissa, 2021; Abebaw, 2025).

Nitrogen is a key nutrient for plants; inadequate application can stunt growth and lower yields in both irrigated and rain-fed systems (Usman, 2020; Negash *et al.*, 2023). In addition of to this, nitrogen application management is also needing more important for proper utilization by plants due to its nature (Ali, *et al.*, 2025). For instance, it can be volatile from the root zone of the crop plant at high temperature, whereas at high water it becomes leach (Sabina, *et al.*, 2025).

In Ethiopia, a remarkable 93% of the country's water resources are used for agriculture, surpassing the global average of 70% (Water and Ethiopia Archive (WEA), 2020). For context, Egypt's agricultural sector utilizses about 85% of its water resources (Gameh *et al.*, 2020). This indicates that Ethiopia's agricultural water consumption exceeds Egypt's by 8%, highlighting the urgent need for better water management practices to boost agricultural productivity and ensure food security. However, inappropriate application of irrigation water in the root zone of crop plants significantly affects the nitrogen use efficiency of the crop plant due to leaching of nitrogen from the root zone (Amare, 2025; Zhao, *et al.*, 2025).

Therefore, managing nitrogen and water effectively is vital for global crop production (Plett *et al.*, 2020; Tahir *et al.*, 2024; Yimer and Tarnawa, 2025. While agriculture is foundational to Ethiopia's economy, its potential is limited by inadequate agronomic practices and significant environmental challenges (Yigezu, 2021). Targeted interventions in nutrient and water management are crucial for achieving sustainable agricultural development and improving food security (Saravanakumar, *et al.*, 2020; Kunlere, 2025).

Wheat is a major staple food worldwide, nourishing around 2.5 billion people (Bentley *et al.*, 2022). In Ethiopia, it is vital for food security and is primarily cultivated by smallholder farmers using rain-fed methods (Abate and Walelign, 2023). However, this system has not adequately addressed food security and self-sufficiency issues. A notable yield gap exists in rain-fed wheat production, with reported gaps of 61%, 55%, and 46% compared to yields from research stations, farmers' plots, and potential yields, respectively (Fisseha *et al.*, 2020).

To tackle these challenges, the Ethiopian government has launched initiatives to boost wheat production through irrigation systems, aiming to improve food security and self-sufficiency (Senbeta and Worku, 2023). Durum wheat significantly increases its grain yield (often >40%), spike number, and biomass under irrigated conditions compared to rain-fed systems, especially in Mediterranean climates (Firew, *et al.*, 2024). However, the lack of appropriate irrigation and agronomic technologies hinders the achievement of high and sustainable yields (Su and Singh, 2024). Additionally, developing new agronomic and irrigation technologies through traditional research takes years. To address these research gaps quickly, there is a pressing need for innovative and accessible technologies, such as computer programs, that can streamline research and facilitate faster solution implementation. By leveraging technology, Ethiopia can enhance wheat production strategies, ultimately improving food security and self-sufficiency.

The Decision Support System for Agro-technology Transfer (DSSAT) is a widely utilized tool for simulating crop growth and yield under various environmental conditions globally (Hussain *et al.*, 2018; Gameh *et al.*, 2020; Chisanga *et al.*, 2021; Hafiza *et al.*, 2022; Aydoğdu *et al.*, 2023; Shawon *et al.*, 2024) and has been applied in Ethiopia (Zerihun *et al.*, 2018; Abu *et al.*, 2019; Endalew, 2019; Silva *et al.*, 2021; Mekides *et al.*, 2022; Bizuwork *et al.*, 2024). However, the model's evaluation under irrigated conditions has not been conducted in central Ethiopia, preventing public recommendations that compare model simulations with actual experimental yields. A more detailed analysis of crop performance can then be performed for various management strategies (soil, plant, irrigation, and fertilizer) and climate change scenarios to identify the most effective and least risky practices.

This study aims to calibrate and evaluate the CERES model for predicting growth and yield of wheat under nitrogen rates and irrigation intervals in central Ethiopia. By comparing model predictions with field data from experimental plots, the study seeks to evaluate the model's effectiveness in predicting wheat yield under various management scenarios.

2. Materials and Methods

2.1. Description of the study area

This study was conducted at Debre Zeit Agricultural Research Centeer (DZARC), which is located at a latitude of 8°48′30″N and a longitude of 38°59′30″E (Figure 1), with an elevation of 1880 meters above sea level (Alemayehu *et al.*, 2024). The soil at the site is vertisol, characterized by a high clay content (52%) and medium levels of silt (24%) and sand (18%). The pH of the soil is 6.61, and it has an organic carbon of 0.1 %. Additionally, the soil has a very low total nitrogen content of 1%, while the medium available phosphorus level was recorded at 23.6 ppm. The average relative humidity in the area is 61.3%, and the average annual rainfall during the experimental years recorded 607 mm. Moreover, the average minimum and maximum temperatures for the study area were 7.9 °C and 26.2 °C, respectively (NMSA, 2024). Monthly rainfall, as well as the distribution of maximum and minimum temperatures during the experimental years, is detailed in Table 1.

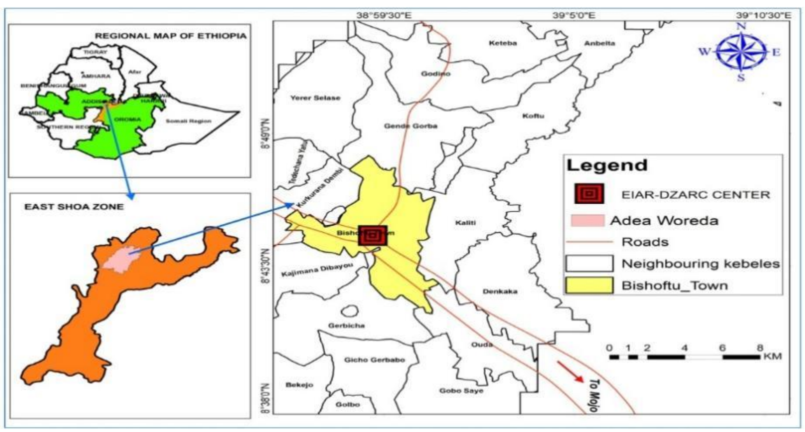

Figure 1. Map of the study site.

Table 1. Rainfall and temperature distribution of the experimental site during the tested years (2022 to 2024 cropping years).

	2022			2023			2024		
	Rainfall	Temp (T ^{0}C)		Rainfall	Temp (T ^{0}C)		Rainfall	Temp (T ^{0}C)	
Months	(mm)	Max.	Min.	(mm)	Max.	Min.	(mm)	Max.	Min
January	15	27	6.1	12	27.1	4.4	0	28	5
February	15	28	7	1.6	28.2	4	0	28.5	4
March	0	29.2	8	1	29.5	6	2	29	5
April	12	30.5	10	10	30.6	6.7	7	31	6
May	10	31.8	8.1	9	32	7.8	15	31	7.4
June	88	29	8.6	74	29.3	9.9	50	30	10
July	190	22.6	10	187	22.8	8	193	22	7
August	155	24	11.1	150	24.4	8.4	127	25	8.5
September	120	25	9.2	112	25.2	10	201	25	9.5
October	0	26.6	7.3	0	27.1	9.1	55	27.4	9
November	0	26.8	4.5	0	27	7.1	10	26.8	7
December	0	26	4.4	0	26.3	4.2	0	26.5	4.5

2.2. Data Sources

2.2.1. Weather data

The weather database utilized daily data on rainfall, minimum and maximum temperature, and solar radiation for the year 2023/24. The datasets were obtained from the National Metrology Station Agency at the DZARC's Climate and Geospatial Department. The monthly rainfall and temperature conditions of the study area are presented in Table 1.

2.2.2.Crop management data

The field experiments were carried out at Debre Zeit in central Ethiopia during the last three consecutive years (2021/22, 2022/23 and 2023/24). One higher grain yielded a durum wheat cultivar, namely "Utuba" (Table 2). It was grown under an irrigated growing environment, which is no stress condition.

Table 2. Description of the cultivar

S/N	Cultivar	Year of release	Altitude (m a.s.l)	Yield (kg ha^{-1})	Representative	Maintaining centers
1	*Utuba*	2015	1800–2650	6025	Higher yielded	DZARC

The crop management data were used for five nitrogen fertilizer rates (0, 46, 92, 138, and 184 kg N ha^{-1}), and three irrigation intervals: I1 (Irrigation water applied every 7-day interval), I2 (Irrigation water applied every 10-day interval), and I3 (Irrigation water applied every 13-day interval). The treatment combinations are listed in Table 3. The experiment was laid out in a split- plot design, with the irrigation intervals serving as the main plot and the nitrogen rate as the subplot, and each was replicated three times. The size of each main plot was 23 meters in length and 4 meters in width (92 m²), while the size of each subplot was 4 meters in length and 3 meters in width (12 m²). The space between main plots and subplots was 3 meters and 2 meters, respectively. Each subplot contained fifteen rows with a spacing of 20 cm between rows. The durum wheat variety was planted with a seed rate of 125 kg ha^{-1}. The recommended phosphorus fertilizer, triple super phosphate (TSP), was applied at a rate of 100 kg ha^{-1} by banding the granules at the time of sowing. The nitrogen fertilizer source, Urea, was applied based on the site recommended in two splits: two-thirds of the urea was applied at tiller initiation and the remaining one-third was applied at the booting stage for all nitrogen rates. The irrigation water applied is indicated in Table 6. Weeds were controlled through hand weeding.

Table 3. Soil physical properties of the experimental soil

Factor	Treatment	Symbolic
Irrigation interval	Every seven days irrigation water apply per cropping year ($7_{interval}$)	I_1
	Every ten days irrigation water apply per cropping year ($10_{interval}$)	I_2
	Every thirteen days irrigation water apply per cropping year($13_{interval}$)	I_3
Urea rates	0 kg N ha^{-1}	N_1
	46 kg N ha^{-1}	N_2
	92 kg N ha^{-1}	N_3
	138 kg N ha^{-1}	N_4
	184 kg N ha^{-1}	N_4
Treatment combination	(I_1N_1, I_1N_2, I_1N_3, I_1N_4 and I_1N_5), (I_2N_1, I_2N_2, I_2N_3, I_2N_4 and I_2N_5),(I_3N_1, I_3N_2, I_3N_3, I_3N_4 and I_3F_5)	

2.2.3. Soil data

The soil samples from the experimental site were collected after land preparation but before planting, from five different locations within the site, using an auger in a zigzag pattern. Samples were taken from five different soil depths, as presented in Tables 4, 5 and 6. The collected soil samples were composited into one sample per individual soil profile and then analyzed using standard analytical methods to determine both the physical and chemical properties of the soil, as well as its water-holding capacity through a hygroscopic test. The results of these analyses are presented in Tables 4, 5 and 6. The physical properties, water-holding capacity, and chemical characterization of the soil, respectively.

Table 4. Soil physical properties of the experimental soil.

Soil physical properties	Soil profile (cm)				
	0 – 20	20 – 40	40 – 60	60 – 90	90 –120
Clay (%)	60	58	50	28	62
Silt (%)	20	22	24	26	28
Sand (%)	10	10	16	46	10
Texture	Clay	Clay	Clay	Clay loam	Clay
Bulk density (g/cm^3)	1.33	1.57	1.44	1.35	1.30

Source = DZARC, Soil laboratory.

Table 5. Soil water holding capacity of the experimental soil

Soil water holding capacity	Soil profile (cm)				
	0 – 20	20 – 40	40 – 60	60 – 90	90 –120
Field capacity (% vol.)	39.35	35.94	39.90	35.44	37.84
Permanent welting point (% vol.)	23.76	24.58	39.90	35.44	37.84
Total available water (mm/m)	207.35	178.35	215.42	137.30	136.24

Source = DZARC soil laboratory.

Table 6. Soil chemical characterization of the experimental soil

Soil chemical characterization	Soil profile (cm)				
	0 – 20	20 – 40	40 – 60	60 – 90	90 –120
pH (1 : 2.5 H_2O)	6.27	6.27	6.26	6.51	7.72
Available P (ppm)	23.6	9.6	2.4	7.2	10.6
Available K (ppm)	258	188	118	90	95
Total N (%)	1	0.71	0.54	0.42	0.21
Organic carbon (%)	0.10	0.08	0.06	0.06	0.03
NO_3^-N (mg kg^{-1})	10.1	7.0	5.5	4.3	2.3
NH4$^+$N (mgkg^{-1})	1.6	1.7	1.7	2.4	2.6
Ex. Ca (cmol(+)kg^{-1})	33.90	33.00	46.51	23.75	33.88
Ex. Mg (cmol(+)·kg^{-1})	8.59	8.36	17.33	5.02	10.70
CEC (cmol(+)kg^{-1})	51.59	51.17	67.41	37.00	49.00

Source = DZARC Soil laboratory. Total N = total nitrogen, P = phosphorus, Ex = exchangeable, and CEC = Cation exchangeable capacity.

2.3. Observed Data Collection

Days to emergence was were determined by counting the days from the date of planting to the date when th land was covered by the plants. Crown root initiation (CRI) stage was determined by counting the days from the date of planting to CRI from ten plants after collection with the help of a spade at a depth of 25 cm depth from the middle portion of each plot. Days to flowering was were recorded by counting the number of days from the date of planting to the date when 90% of the head (spike) was flowered. Leaf area was measured at crown root initiation, maximum tillering, booting stage, anthesis, and physiological maturity by an automatic area meter (LI 3100 C, LI-COR, USA). For dry matter partitioning of leaves, stem, and reproductive part (spike) were separated and dried in an oven at 70^{o}C for 72 hours. The number of productive tillers per plant was counted from the plants grown at 0.1 m2 of the net plot area. The number of spikelets per spike was recorded from ten randomly taken plants grown in the net plot area and the mean number of spikelets per spike was computed and used for analysis. Similarly, the average number of kernels per spike was recorded by counting the kernels per spike of ten randomly taken plants grown at in the net plot area. Aboveground biomass yield (kg ha^{-1}) was determined by weighting the total aboveground parts of the plants harvested from the net plot area. The harvested biomass was dried for 72 hours in natural sunlight and weighed in kilograms and expressed in kilograms per hectare. Grain yield (kg ha^{-1}) was obtained by trashing plants grown at the length of 5 m and the width of 4 m (20 m2) of the net plot area. The grains were weighed using a sensitive balance and expressed in kilograms per hectare.

2.4. DSSAT Model

Decision Support System for Agro-technology Transfer (DSSAT-CERES-Wheat) v4.8.5 was used to simulate growth and yield of three durum wheat cultivars under irrigated growing environments of Ethiopia. For the running of the model, three sets of data were used that included Soil, weather, and crop management files. Soil data contend contain soil physical and chemical properties such as soil type and soil series, pH, bulk density, soil texture, total nitrogen and organic carbon content also included as well as the site latitude and longitude. The Weather file also included maximum temperature, minimum temperature, humidity, solar radiation, and rainfall. DSSAT model required some of crop management data sheets (X-build) which included File Sheet (Experimental name, Institution code, Site code, Year, Experiment number, and Crop), Environmental Sheet (Fields, Initial conditions, Soil analysis, Environmental modifications) and Management Sheet (Cultivar, Planting (date, method, distribution, population, spacing, direction, and depth), Irrigation, Fertilizer, Organic amendments, Tillage, Harvesting, Chemical application (Menefee *et al.*, 2021) in experimental file to simulate crop growth and productivity. Data on physiological stages of crop growth and phenology, such as planting date, days to anthesis, days to maturity, leaf area index, root growth, plant height and grain yield, were also included in A and T–files.

The crop management data were recorded throughout the growing seasons. The input files, such as the weather file, soil file, A–file, and T–file, were created for running the model. The model was calibrated with a set of field experimental data and subsequently validated with another dataset of field experiments. The genetic coefficients were obtained by using the GLUE coefficients estimator method. GLUE is one of the DSSAT programs used for estimating specific parameters of a variety. Seven characters of wheat were needed in the CERES-Wheat model in DSSAT (Table 7).

Table 7. Genetic coefficients of the DSSAT-CERES-Wheat model

Coefficient	Definition
P1V	Days, optimum vernalizing temperature, required for vernalization
P1D	Photoperiod response (% reduction in rate/10 h drop in pp)
P5	Grain filling (excluding lag) phase duration (degree day)
G1	Kernel number per unit canopy weight at anthesis (kernel number/m^2)
G2	Standard kernel size under optimum conditions (mg)
G3	Standard, non-stressed dry weight (total, including grain) of a single tiller at maturity (gdwt)
PHINT	Thermal time between the appearance of leaf tips (degree days)

2.5. Model Calibration and Evaluation

The statistical indicators used for performance evaluated include Root Mean Square Error (RMSE): Indicates absolute error; low values (< 10-20%) indicate high accuracy. Normalized RMSE (nRMSE): Percentage error for better comparison across different crops. Coefficient of Determination (R^2): Measures the correlation between observed and simulated values. Agreement Index (d): Measures accuracy (closer to 1 is better). Percentage Error (PE%): Percent difference between simulated and observed yield (e.g., often found within 10-15%) (Nakagawa *et al.*, 2017; Endalew, 2019, Li *et al.*, 2020). These statistical measures are described as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2}$$

$$nRMSE = \frac{RMSE}{\bar{O}} \times 100$$

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}}\right)^2$$

$$d = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2}$$

Where: S_i**:** The ith simulated value from the model, O_i**:** The ith observed value from the field: **n:** The total number of observations; ∑**:** the Summation symbol; $\bar{O}$**:** Mean of observed data and **d:** Index of agreement.

2.6. Model Parameterization and Calibration

To accurately record the simulation results of the tested DSSAT–crop models under different agronomic experiments, the exact genetic coefficients of the tested cultivar are required. These coefficients are specific to cultivar and describe processes related to growth, development, and grain production (Chen *et al.,* 2021). The genetic coefficients enable the model to simulate the performance of diverse genotypes under varying soil, weather, and management conditions (Jha *et al.,* 2023). The model was calibrated using previously observed values measured from the field, along with weather parameters, crop management practices, and soil properties during the 2021/22, cropping season at DZARC. Genetic coefficients were calculated based on the observed days to anthesis and physiological maturity, leaf area index, and grain yield of the tested cultivar from the 2021/22cropping season at DZARC.

However, the durum wheat cultivar was not included in the DSSAT genotype file, necessitating the start of the calibration process by determining the genetic coefficients of this cultivar. Initial genetic coefficient values were obtained from the model cultivar known as MARIS FUNDIN (cultivar from the model), which are already available in DSSAT. The computed CSP values for the test cultivar was were copied into the cultivar (CUL) file to facilitate the simulation. The genetic coefficients were determined using the GLUE coefficients estimator method, which was run up to 10,000 times until a match was achieved between the observed and simulated dates of anthesis and physiological maturity, leaf area index, production tillers per group, and grain yield. The GLUE is one of the DSSAT programs used for estimating genetic coefficients for specific cultivars (Ibrahim *et al.,* 2016). The identified genetic coefficients were subsequently used for model evaluation.

2.7. Model Evaluation

Model evaluation indicated the process of comparing the model and its behavior to the observed data (Ahmed *et al.,* 2020; Janghel and Puranik, 2023). In this study, the performance of the calibrated model was evaluated by comparing the simulated values to the observed values from the experiments conducted in 2022/23 and 2023/24. Data for model evaluation included days to emergence, days to anthesis, days to physiological maturity, leaf area index, grain yield, and harvest index. The accuracy of the model simulations was assessed based on the predicted deviation (the difference between the predicted and observed values in percentage). A model is considered to perform well when the percent difference (PD) (Candela *et al.,* 2000; Nikhil *et al.,* 2024).

3. Results and Discussion

3.1. Model Calibration

Model calibration indicators of goodness of fit for crop phenology and yield of one durum wheat cultivar for DSSAT–CERES–Wheat module and the genetic coefficients of the durum wheat cultivar obtained using the GLUE program and are shown in Tables 8 and 9. These genetic coefficients were derived from the field trial data of the tested durum wheat cultivar "*Utuba*" for the one year 2021/22. The genetic coefficient P1V for the cultivars Utuba was 10 days. This result indicates that the tested durum wheat cultivar grown in Ethiopia requires vernalization, as this cultivar was of the winter wheat type (Bega). The photoperiod coefficient (genetic coefficient P1D) for Utuba cultivar was 20. The tested cultivar exhibited variation in the grain filling period coefficient, with the cultivar Utuba showing the value of 380 degree days.

The genetic coefficient G1 for the cultivar Utuba was 11 kernel numbers/m². Additionally, the genetic coefficient G2 for this cultivar was 79 mg. The PHINT (80 degree days) was observed in the tested cultivar. The G3 value of Utuba was 0.8 g (see Table 8). The genetic coefficients obtained from the current research categorized durum wheat as a winter wheat type, as stated by Aydoğdu *et al.* (2023). The photoperiod coefficient (P1V), photoperiod coefficient (P1D), grain filling period (P5), spike number coefficient (G1), standard head weight (G2), standard grain weight (G3), and days in development (PHINT) ranged from 5–60, 54–58%, 221–350, 15–50 kg^{-1}, 33–79 mg, 1.5–2.9 g, and 95–110 days, respectively, which are desirable for winter wheat cultivars

.

Table 8. Model calibration indicators of goodness of fit for crop phenology and yield of durum wheat cultivar for DSSAT–CERES–Wheat module under irrigated growing environment

Cultivar	Parameters	Obs.	Sim.	PE (%)	R^2	nRMSE (%)	d
	Days to maturity (days)	113	117	3.4	0.98	2.0	0.97
	Grain yield (kg/ha)	6000	6401	6.3	0.85	4.2	0.85
Utuba	Biomass yield (kg/ha)	11700	12300	4.9	0.99	3.0	0.89
	Straw yield (kg/ha)	5700	5899	3.4	0.97	0.7	0.92
	Harvest index (%)	51	52	1.9	0.99	2.6	0.98

Obs.=Observed, Sim.=Simulated, PE=Percent error differences, R2=coefficient of determination, nRMSE= normalized root-mean square error, and d= index of agreement

Table 9. Genetic coefficient of the durum wheat cultivar.

Coefficients	Utuba
P1V (Days)	10
P1D (% reduction in rate $10h^{-1}$ drop in pp)	20
P5 (degree day)	380
G1 (kernel Number/m^2)	11
G2 (milligram)	79
G3 (g dwt)	0.8
PHINT (degree day)	80

3.2. Model Evaluation

3.2.1. Days to heading

The model evaluation summarized in Table 10 revealed that the estimated number of days to heading were consistently longer than the observed values, by 0.5 to 4 days in the 2022/23 season and 1 to 4.5 days in 2023/24, across all nitrogen and irrigation treatment combinations. Among all interactions analyzed, the model predicted a greater number of days to heading compared to the actual data, highlighting the model's efficacy in simulating durum wheat heading times under varying nitrogen fertilizer applications in irrigated conditions. The study found that the DSSAT-CERES-Wheat model provided reliable simulations of days to heading influenced by different nitrogen rates and irrigation intervals, as outlined in Table 10.

The nRMSE percentages, R^2 values, and d-stat ranged from 0.81 to 6.56%, 0.65 to 0.91, and 0.55 to 0.85 during 2022/23, and 1.75 to 8.57%, 0.58 to 0.89, and 0.54 to 0.75 in 2023/24, respectively. These results indicate that the model accurately predicts the days to heading for durum wheat, with acceptable nRMSE values below 10%, R^2 ranging from 0.43 to 0.99, and d-stat values between 0.52 and 0.99. Literature supports the model's reliability, as previous studies by Elgadi (2019) and Endalew (2019) confirmed its effectiveness in predicting heading times across various agronomic practices and climatic conditions.

Table 10. Indicators of goodness of fit for days to heading of Utuba durum wheat cultivar for DSSAT–CERES–Wheat model.

Treatments		2022/23						2023/24					
Irrigation Intervals	N-rate (kg ha^{-1})	Obs	Sim	ED	R^2	nRMSE %	d-stat	Obs	Sim	ED	R^2	nRMSE %	d-stat
Irrigation-1 (I_1)	0	56	58	+2	0.84	3.57	0.69	51.5	53	+1.5	0.86	2.91	0.70
	46	58	61	+3	0.75	5.2	0.60	57	58	+1	0.89	1.75	0.75
	92	61	65	+4	0.67	6.56	0.55	58.5	60	+1.5	0.85	2.56	0.69
	138	62	66	+4	0.65	6.45	0.58	61	64	+3	0.76	4.92	0.61
	184	65	68	+3	0.79	4.62	0.66	64	67	+3	0.77	4.69	0.63
Irrigation-2 (I_2)	0	55	56	+1	0.86	1.81	0.78	51	55	+4	0.63	7.84	0.55
	46	57	60	+3	0.76	5.26	0.61	55.3	59	+3.7	0.65	6.69	0.54
	92	59.5	62	+2.5	0.80	4.2	0.67	57.5	60	+2.5	0.79	4.35	0.65
	138	61.5	64	+2.5	0.79	4.07	0.68	60.3	64	+3.7	0.64	6.14	0.59
	184	64	67	+3	0.75	4.69	0.65	62	66	+4	0.60	6.45	0.57
Irrigation-3 (I_3)	0	54	56	+2	0.83	3.7	0.67	48	50	+2	0.81	4.17	0.66
	46	56.5	58	+1.5	0.85	2.65	0.75	52	54	+2	0.80	3.85	0.68
	92	59	61	+2	0.84	3.39	0.70	52.5	57	+4.5	0.58	8.57	0.54
	138	61.5	62	+0.5	0.91	0.81	0.85	59.5	61	+1.5	0.87	2.52	0.71
	184	63	65	+2	0.83	3.17	0.72	60	63	+3	0.76	5	0.60

Obs.= Observed, Sim.= Simulated, ED=Error differences, R2=coefficient of determination, nRMSE= normalized root-mean square error, and d-stat= index of agreement. Irrigation-1= Application of irrigation water every seven days' interval), Irrigation-2= Application of irrigation water every ten days' interval and irrigation-3= Application of irrigation water every thirteen days' interval.

3.2.2 Physiological maturity

The model evaluation results showed that the estimated days to physiological maturity were consistently 1.5 to 4 days and 1 to 4 days longer than the observed values across all treatment combinations in the 2022/23 and 2023/24 cropping seasons, respectively (Table 11). The study indicated that the simulated model recorded the highest number of days to physiological maturity compared to the observed data (Table 11). This highlights the effectiveness of the DSSAT-CERES-Wheat model in simulating the days to physiological maturity of the Utuba durum wheat cultivar. However, the model's effectiveness is assessed through the normalised root mean square error (nRMSE %), coefficient of determination (R^2), and index of agreement (d-stat) values. The analysis revealed that during the 2022/23 season, the nRMSE % ranged from 1.44 to 4.08%, R^2 from 0.68 to 0.97, and d-stat from 0.60 to 0.85. In the 2023/24 season, these values ranged from 0.95 to 4.26%, 0.80 to 0.98, and 0.64 to 0.81, respectively (Table 11). These results indicate a reliable simulation of the days to physiological maturity in response to different nitrogen rates and irrigation intervals.

Accurate simulation of physiological maturity is essential for predicting subsequent crop growth and yield. Previous studies, such as those by Elgadi (2019), support the model's effectiveness in predicting physiological maturity under various agricultural practices and climatic conditions. In conclusion, while the DSSAT-CERES-Wheat model shows strong potential for simulating physiological maturity in durum wheat based on nitrogen rates and irrigation intervals, it tends to slightly overestimate the time to maturity, suggesting the need for future model refinements to enhance accuracy.

Table 11. Indicators of goodness of fit for days to physiological maturity of Utuba durum wheat cultivar for DSSAT–CERES–Wheat model evaluation as influenced by nitrogen rates and irrigation intervals during 2022/23 and 2023/24 cropping seasons

Treatments		2022/23						2023/24					
Irrigation Intervals	N-rate (kg ha^{-1})	Obs	Sim	ED	R^2	nRMSE %	d-stat	Obs	Sim	ED	R^2	nRMSE %	d-stat
Irrigation-1 (I_1)	0	97	100	+ 3	0.76	3.05	0.72	94	98	+4	0.80	4.26	0.65
	46	104	108	+ 4	0.71	3.77	0.68	97.5	100	+2.5	0.87	2.56	0.72
	92	108	111	+ 3	0.84	2.74	0.75	103	105	+2	0.93	1.94	0.78
	138	110	112	+ 2	0.95	1.80	0.82	105.5	107	+1.5	0.94	1.42	0.73
	184	113	115	+ 2	0.96	1.75	0.84	108	111	+3	0.86	2.78	0.69
Irrigation-2 (I_2)	0	96	100	+ 4	0.68	4.08	0.60	93	96	+3	0.83	3.25	0.67
	46	104	105	+ 1.5	0.97	1.44	0.85	97	99	+2	0.89	2.06	0.70
	92	105	107	+ 2	0.94	1.89	0.80	102	104	+2	0.91	1.95	0.75
	138	106	110	+ 4	0.72	3.70	0.70	104	105	+1	0.96	0.96	0.81
	184	109	111	+ 2	0.95	1.82	0.81	105	106	+1	0.98	0.95	0.79
Irrigation-3 (I_3)	0	95	98	+ 3	0.75	3.11	0.71	90	93	+3	0.81	3.33	0.64
	46	97.5	100	+ 2.5	0.89	2.53	0.77	96	97	+1	0.95	1	0.75
	92	98	102	+ 4	0.70	4.00	0.65	98	100	+2	0.90	2.04	0.77
	138	100	103	+ 3	0.82	2.96	0.73	99	102	+3	0.82	3.03	0.71
	184	102	104	+ 2	0.90	1.94	0.79	101	104	+3	0.84	2.97	0.73

Obs.= Observed, Sim.= Simulated, ED=Error differences, R2=coefficient of determination, nRMSE= normalized root-mean square error, and d-stat= index of agreement. Irrigation-1= Application of irrigation water every seven days' interval), Irrigation-2= Application of irrigation water every ten days' interval and irrigation-3= Application of irrigation water every thirteen days' interval.

3.2.3. Plant height

Notably, the simulated plant height of the Utuba cultivar exceeded the observed height across all nitrogen treatments in both irrigation intervals (Table 12). At zero nitrogen fertilizer rates with I3 (I3N1), the plant height of the Utuba cultivar was significantly lower compared to other nitrogen and irrigation treatments. In contrast, the highest plant height for both simulated and observed values was achieved with the application of 184 kg N ha^{-1} and irrigation every seven days (I1) (I1N5) (Table 12). Additionally, I3 combined with zero nitrogen resulted in the shortest plant height for the Utuba cultivar.

The quality of the model simulation is mainly assessed through the normalizsed root mean square error (nRMSE %), the coefficient of determination (R^2), and the index of agreement (d-stat). For the Utuba cultivar's plant height, the NRMSE % ranged from 2.04 to 7.94%, R^2 from 0.67 to 0.94, and d-stat from 0.50 to 0.75 during the 2022/23 cropping season. In the 2023/24 cropping season, these values ranged from 1.94 to 7%, 0.68 to 0.89, and 0.51 to 0.72, respectively (Table 12). These results indicate that the model simulation is reliable for predicting plant height affected by various nitrogen rates and irrigation intervals.

Thus, the DSSAT-CERES-wheat model effectively simulates the plant height of the Utuba cultivar (Table 12) and is suitable for predicting future plant height under different agronomic management conditions. Previous studies have also highlighted the DSSAT-CERES-wheat model's importance in providing accurate plant height predictions across diverse agronomic, soil, and climatic scenarios (Wei *et al.,* 2022; Yang *et al.,* 2024).

Table 12. Indicators of goodness of fit for plant height of Utuba durum wheat cultivar for DSSAT–CERES–Wheat model evaluation as influenced by nitrogen rates and irrigation intervals during 2022/23 and 2023/24 cropping seasons

Treatments		2022/23						2023/24					
Irrigation Intervals	N-rate (kg ha^{-1})	Obs	Sim	ED	R^2	nRMSE %	d-stat	Obs.	Sim	ED	R^2	nRMSE %	d-stat
Irrigation-1 (I_1)	0	76	80	+4	0.80	5.26	0.63	73	77	+4	0.79	5.48	0.60
	46	98	100	+2	0.94	2.04	0.75	96	99	+3	0.83	3.13	0.63
	92	103	109	+6	0.73	5.83	0.54	100	107	+7	0.68	7	0.51
	138	108	113	+5	0.87	4.63	0.71	105	110	+5	0.77	4.76	0.57
	184	109	114	+5	0.90	4.59	0.72	106	112	+6	0.71	5.66	0.55
Irrigation-2 (I_2)	0	72	75	+3	0.92	4.17	0.74	70.7	73	+2.3	0.86	3.25	0.68
	46	97	102	+5	0.82	5.15	0.64	95	99	+4	0.80	4.21	0.61
	92	100	105	+5	0.84	5	0.67	97	102	+5	0.76	5.15	0.58
	138	105	110	+5	0.86	4.76	0.70	103	105	+2	0.87	1.94	0.70
	184	105	111	+5.7	0.77	5.41	0.62	103.7	107	+3.3	0.81	3.18	0.60
Irrigation-3 (I_3)	0	63	68	+5	0.67	7.94	0.50	64	67	+3	0.84	4.69	0.64
	46	83	89	+6	0.70	7.23	0.52	84	88	+4	0.81	4.76	0.62
	92	88	93	+5	0.75	5.68	0.59	89	91	+2	0.89	2.25	0.72
	138	91	96	+5	0.76	5.49	0.60	92	95	+3	0.85	3.26	0.65
	184	94	100	+6	0.71	6.38	0.53	95	99	+4	0.80	4.21	0.62

Obs.= Observed, Sim.= Simulated, ED=Error differences, R2=coefficient of determination, nRMSE= normalized root-mean square error, and d-stat= index of agreement. Irrigation-1= Application of irrigation water every seven-days' interval), Irrigation-2= Application of irrigation water every ten days' interval and irrigation-3= Application of irrigation water every thirteen days' interval**.**

3.2.4. Grain yield

The current model evaluations the effects of nitrogen rates and irrigation intervals on grain yield, as shown in Table 13. The results indicate that the model accurately predicted grain yield for all treatments tested. The Utuba cultivar achieved the highest simulated grain yields of 7257 kg ha^{-1} and 6930 kg ha^{-1} with the application of 138 kg N ha^{-1} and irrigation every seven days (I1) during the 2022/23 and 2023/24 cropping seasons, respectively. In contrast, the lowest simulated yields of 378 kg ha^{-1} and 490 kg ha^{-1} were observed with no nitrogen application and irrigation every thirteen days (I3) during the same years.

Over the two years, the coefficient of determination (R^2) for simulated and observed grain yields ranged from 0.65 to 0.89 in 2022/23, and from 0.60 to 0.87 in 2023/24. The normalizsed root-mean square error (nRMSE %) for these yields ranged from 2.26% from I2 with 184 kg N/ha to 23.01% from I3 without N-fertilizer in 2022/23, and from 3.09% from I1 and 92 kg N/ha to 22.5% from I3 without N-fertilizer in 2023/24 (Table 13). Normalized root-mean square error (nRMSE%) and coefficient of determination (R^2) are the most model performance indicates commonly used metrics. According to Choudhury *et al.* (2018) and Aydoğdu *et al.* (2023), nRMSE values are categorized as very good (< 10%), good (10–20%), fair (20–30%), and poor (> 30%) and the result of R^2 values for winter wheat ranged from 0.43 to 0.99 (Wang *et al.*, 2024). Therefore, the nRMSE values of the present study was rated between very good and good at different irrigation and nitrogen levels, except making fair predictions at the I3 irrigation level without nitrogen application, both in the 2022/23 and 2023/24 cropping seasons. The result of R^2 values for winter wheat ranged from 0.43 to 0.99 (Xia *et al.*, 2015; Wang *et al.*, 2024) For wheat, R^2 values have been reported between 0.43 and 0.99 (Wang *et al.*, 2024).

The recorded R^2 and nRMSE% values align with previous findings, suggesting that the model provides reliable predictions. Thus, the model's simulated R^2 and nRMSE values across all nitrogen rates are effective for forecasting future grain yield under various agronomic practices and climate conditions. Previous studies have also noted that the DSSAT-CERES-wheat model is capable of predicting wheat grain yield based on nitrogen rates and irrigation frequency (Sen *et al.*, 2017; Araya *et al.*, 2019).

Table 13. Indicators of goodness of fit for grain yield of *Utuba* durum wheat cultivar for DSSAT–CERES–Wheat model evaluation as influenced by nitrogen rates and irrigation intervals during 2022/23 and 2023/24 cropping seasons.

Treatments		2022/23						2023/24					
Irrigation Intervals	N-rate (kg ha^{-1})	Obs	Sim	ED	R^2	nRMSE %	d-stat	Obs	Sim	ED	R^2	nRMSE %	d-stat
Irrigation-1 (I_1)	0	1500	1595	+ 95	0.76	6.14	0.70	900	980	+80	0.71	8.89	0.62
	46	2400	2525	+ 125	0.80	5.08	0.75	2100	2283	+183	0.74	8.71	0.65
	92	5700	5867	+ 167	0.89	2.89	0.81	5400	5567	+167	0.87	3.09	0.78
	138	7000	7257	+ 257	0.84	3.61	0.78	6700	6930	+230	0.85	3.43	0.76
	184	6800	7081	+ 281	0.82	4.04	0.76	6300	6701	+401	0.80	6.37	0.71
Irrigation-2 (I_2)	0	1000	1158	+ 158	0.71	14.0	0.62	700	760	+60	0.75	8.57	0.66
	46	2100	2235	+ 135	0.75	6.23	0.69	1800	1966	+166	0.68	9.22	0.59
	92	4800	5071	+ 271	0.78	5.49	0.72	4800	5080	+280	0.81	5.83	0.72
	138	6600	6832	+ 232	0.85	3.45	0.80	6000	6550	+550	0.65	9.12	0.56
	184	6400	6546	+ 146	0.91	2.26	0.85	5700	6067	+360	0.79	6.44	0.70
Irrigation-3 (I_3)	0	300	378	+ 78	0.65	23.01	0.55	400	490	+90	0.60	22.5	0.51
	46	1000	1126	+ 126	0.72	11.85	0.65	1100	1200	+100	0.70	9.09	0.60
	92	1200	1423	+ 223	0.67	17.00	0.58	1500	1610	+110	0.77	7.33	0.68
	138	1900	2134	+ 234	0.73	11.60	0.66	3400	3675	+275	0.76	8.08	0.67
	184	1600	1849	+ 249	0.70	14.44	0.60	2500	2680	+180	0.78	7.2	0.69

Obs.= Observed, Sim.= Simulated, ED=Error differences, R2=coefficient of determination, nRMSE= normalized root-mean square error, and d-stat= index of agreement. Irrigation-1= Application of irrigation water every seven days' interval), Irrigation-2= Application of irrigation water every ten days' interval and irrigation-3= Application of irrigation water every thirteen days' interval.

3.2.4. Biomass yield

This study presents the biomass yield simulation results from the DSSAT-CERES-Wheat model, considering the effects of irrigation intervals and nitrogen rates, as shown in Table 14. The differences between the simulated and observed biomass yields, affected by the interaction of nitrogen rates and irrigation intervals, are detailed in the same table. During the 2022/23 cropping year, the simulated biomass yield varied from 3516 to 17690 kg ha^{-1} for I1, 2581 to 15434 kg ha^{-1} for I2, and 1402 to 7897 kg ha^{-1} for I3. In the 2023/24 cropping year, the yields ranged from 2280 to 16500 kg ha^{-1} under I1, 1750 to 14300 kg ha^{-1} under I2, and 1110 to 3850 kg ha^{-1} under I3.

The highest simulated biomass yield of 17690 kg ha^{-1} was achieved with 138 kg N ha^{-1} under I1, while the lowest yield of 1110 kg ha^{-1} occurred with no nitrogen applied under I3, for both simulated and observed values. Additionally, the normalized root means square error (nRMSE %), coefficient of determination (R^2), and index of agreement (d-stat) for the Utuba cultivar's simulated biomass yield ranged from 0.71 to 15.53%, 0.65 to 0.96, and 0.56 to 0.87 during 2022/23, and from 7.64 to 16.84%, 0.63

to 0.83, and 0.50 to 0.79 during 2023/24, respectively. These findings suggest that the model is suitable for simulating biomass yields influenced by varying nitrogen rates and irrigation intervals, as well as other agronomic practices. Previous research has similarly shown that the DSSAT-CERES-Wheat model is vital for accurately predicting biomass yields under different agronomic and climatic conditions (Sen *et al.*, 2017; Zain *et al.*, 2023).

Table 14. Indicators of goodness of fit for biomass yield of *Utuba* durum wheat cultivar for DSSAT–CERES–Wheat model evaluation as influenced by nitrogen rates and irrigation intervals during 2022/23 and 2023/24 cropping seasons.

Treatments		2022/23						2023/24					
Irrigation Intervals	N-rate (kgha^{-1})	Obs.	Sim.	ED	R^2	nRMSE %	d-stat	Obs.	Sim.	ED	R^2	nRMSE %	d-stat
Irrigation-1 (I_1)	0	3440	3516	+ 76	0.70	2.19	0.70	2070	2280	+210	0.69	10.14	0.69
	46	6000	6158	+ 158	0.89	2.60	0.78	4830	5310	+480	0.71	9.94	0.70
	92	14100	14201	+ 101	0.96	0.71	0.87	12420	13600	+1180	0.74	9.5	0.73
	138	17500	17690	+ 190	0.93	1.01	0.84	15200	16500	+1300	0.80	8.55	0.79
	184	17000	17185	+ 185	0.92	1.08	0.82	14400	15500	+1100	0.83	7.64	0.71
Irrigation-2 (I_2)	0	2300	2581	+ 281	0.69	11.51	0.60	1540	1750	+210	0.68	13.6	0.53
	46	5100	5319	+ 219	0.78	4.20	0.69	3960	4320	+360	0.76	9.09	0.65
	92	11000	11300	+ 300	0.85	2.69	0.76	10500	11500	+1000	0.74	9.52	0.63
	138	15200	15434	+ 234	0.91	1.53	0.80	13100	14300	+1200	0.75	9.16	0.64
	184	14700	14853	+ 153	0.92	1.04	0.81	12540	13600	+1060	0.81	8.45	0.70
Irrigation-3 (I_3)	0	1200	1402	+ 202	0.65	15.53	0.56	950	1110	+160	0.63	16.84	0.50
	46	3700	3916	+ 216	0.75	5.67	0.65	2510	2750	+240	0.72	9.56	0.61
	92	4800	4880	+ 80	0.88	1.65	0.79	3500	3850	+350	0.70	10	0.59
	138	7600	7897	+ 297	0.81	3.83	0.69	7800	8560	+760	0.71	9.74	0.60
	184	6400	7015	+ 615	0.71	9.17	0.58	5900	6465	+565	0.73	9.58	0.62

Obs.= Observed, Sim.= Simulated, ED=Error differences, R2=coefficient of determination, nRMSE= normalized root-mean square error, and d-stat= index of agreement. Irrigation-1= Application of irrigation water every seven days' interval), Irrigation-2= Application of irrigation water every ten days' interval and irrigation-3= Application of irrigation water every thirteen days' interval

3.2.5. Straw yield

This study presents the biomass yield simulation results from the DSSAT-CERES-Wheat model, considering the effects of irrigation intervals and nitrogen rates, as shown in Table 14. The differences between the simulated and observed biomass yields, affected by the interaction of nitrogen rates and irrigation intervals, are detailed in the same table. During the 2022/23 cropping year, the simulated biomass yield varied from 3516 to 17690 kg ha^{-1} for I1, 2581 to 15434 kg ha^{-1} for I2, and 1402 to 7897 kg ha^{-1} for I3. In the 2023/24 cropping year, the yields ranged from 2280 to 16500 kg ha^{-1} under I1, 1750 to 14300 kg ha^{-1} under I2, and 1110 to 3850 kg ha^{-1} under I3.

The highest simulated biomass yield of 17690 kg ha^{-1} was achieved with 138 kg N ha^{-1} under I1, while the lowest yield of 1110 kg ha^{-1} occurred with no nitrogen applied under I3, for both simulated and observed values. Additionally, the normalized root mean square error (nRMSE %), coefficient of determination (R^2), and index of agreement (d-stat) for the Utuba cultivar's simulated biomass yield ranged from 0.71 to 15.53%, 0.65 to 0.96, and 0.56 to 0.87 during 2022/23, and from 7.64 to 16.84%, 0.63 to 0.83, and 0.50 to 0.79 during 2023/24, respectively. These findings suggest that the model is suitable for simulating biomass yields influenced by varying nitrogen rates and irrigation intervals, as well as other agronomic practices. Previous research has similarly shown that the DSSAT-CERES-Wheat model is vital for accurately predicting biomass yields under different agronomic and climatic conditions (Sen *et al.*, 2017; Zain *et al.*, 2023).

Table 15. Indicators of goodness of fit for straw yield of *Utuba* durum wheat cultivar for DSSAT–CERES–Wheat model evaluation as influenced by nitrogen rates and irrigation intervals during 2022/23 and 2023/24 cropping seasons

Treatments		2022/23						2023/24					
Irrigation Intervals	N-rate ($kgha^{-1}$)	Obs.	Sim.	ED	R^2	nRMSE %	d-stat	Obs.	Sim.	ED	R^2	nRMSE %	d-stat
Irrigation-1 (I_1)	0	1940	2135	+195	0.75	10.05	0.61	1170	1300	+130	0.73	11.11	0.58
	46	3600	3900	+300	0.87	8.33	0.73	2730	3000	+270	0.75	9.89	0.60
	92	8400	9000	+600	0.89	7.14	0.75	7020	7600	+580	0.83	8.26	0.68
	138	10500	11500	+1000	0.80	9.52	0.66	8500	9000	+500	0.90	5.88	0.75
	184	10200	11160	+960	0.81	9.41	0.67	8100	8900	+800	0.76	9.87	0.61
Irrigation-2 (I_2)	0	1300	1450	+150	0.72	11.54	0.58	840	950	+110	0.70	13.09	0.55
	46	3000	3260	+260	0.87	8.67	0.73	2160	2350	+190	0.82	8.79	0.67
	92	6200	6800	+600	0.78	9.68	0.64	5700	6000	+300	0.92	5.26	0.77
	138	8600	9000	+400	0.94	4.65	0.80	7100	7800	+700	0.77	9.86	0.62
	184	8300	8900	+600	0.86	7.23	0.72	6840	7500	+660	0.78	9.65	0.60
Irrigation-3 (I_3)	0	900	1030	+130	0.70	14.44	0.56	550	630	+80	0.68	14.55	0.53
	46	2700	2900	+200	0.85	7.41	0.71	1410	1500	+90	0.86	6.38	0.71
	92	3600	3800	+200	0.93	5.56	0.79	2000	2160	+160	0.85	8	0.70
	138	5700	6100	+400	0.90	7.02	0.76	4400	4800	+400	0.80	9.09	0.65
	184	4800	5000	+200	0.98	4.17	0.84	3400	3650	+250	0.87	7.35	0.72

Obs.= Observed, Sim.= Simulated, ED=Error differences, R2=coefficient of determination, nRMSE= normalized root-mean square error, and d-stat= index of agreement. Irrigation-1= Application of irrigation water every seven days' interval), Irrigation-2= Application of irrigation water every ten days' interval and irrigation-3= Application of irrigation water every thirteen days' interval.

3.3. Model Quality

Quality in model simulation is assessed using several metrics: Percent of Normalizsed Root Mean Square Error (nRMSE%), Coefficient of Determination (R^2), and Index of Agreement (d) (Nakagawa *et al.*, 2017; Endalew, 2019; Li *et al.*, 2020). For a model simulation to be considered of good quality, specific thresholds must be met: an nRMSE% value of less than 10% indicates very good quality, 10–20% indicates good quality, 20–30% indicates fair quality, and over 30% signifies poor quality (Choudhury et al., 2018; Aydoğdu *et al.*, 2023). The Coefficient of Determination (R^2) measures how closely the simulated values correlate with observed values in crop models (Dar *et al.*, 2023). In the DSSAT model, acceptable R^2 values for winter wheat range from 0.43 to 0.99 (Xia *et al.*, 2015; Wang *et al.*, 2024). Similarly, the Index of Agreement (d) is another statistical tool used to evaluate the alignment between simulated and observed values in crop models (Gameh *et al.*, 2020; Saldaña and Cotes, 2021).

Current research findings reveal the nRMSE%, R^2, and d-stat values for measured and simulated data related to days to heading, days to physiological maturity, plant height, grain yield, biomass yield, and straw yield, as shown in Tables 10, 11, 12, 13, 14, and 15. This research focused on simulating the phenology, growth, and yield of the Utuba durum wheat cultivar under varying nitrogen rates and irrigation intervals (Tables 10, 11, 12, 13, 14, and 15). Overall, the results indicated that for all tested parameters (days to heading, days to physiological maturity, plant height, grain yield, biomass yield, and straw yield), the nRMSE%, R^2, and d-stat values fell within acceptable ranges established by prior research. Consequently, the model simulation values for these parameters, influenced by nitrogen rates and irrigation intervals, demonstrate high quality and are regarded as acceptable.

4. Conclusion

The normalizsed root mean square error (nRMSE%), coefficient of determination (R^2), and index of agreement (d-stat) assess model performance. This study used the DSSAT–CERES Wheat model to predict durum wheat phenology, growth, and yield under different nitrogen rates and irrigation intervals. Evaluation of the "Utuba" cultivar during 2022/23 and 2023/24 showed that these metrics indicated very good to good model performance. In 2022/23, for days to maturity, nRMSE% ranged from 1.44 to 4.08%, R^2 from 0.68 to 0.97, and d-stat from 0.60 to 0.85. In 2023/24, the same parameters ranged from 0.95 to 4.26%, 0.80 to 0.98, and 0.64 to 0.81, respectively. Plant height predictions showed nRMSE% between 2.04 and 7.94%, R^2 from 0.67 to 0.94, and d-stat from 0.50 to 0.75 in 2022/23, with similar ranges in 2023/24. Grain yield R^2 values ranged from 0.65 to 0.89, with nRMSE% from 2.89% to 23.01% in 2022/23, and from 0.60 to 0.87 R^2 and 3.09% to 22.5% nRMSE% in 2023/24. Biomass yield showed nRMSE% from 0.71 to 15.53% (2022/23) and 7.64 to 16.84% (2023/24), with R^2 from 0.63 to 0.96. Straw yield metrics were similar, with nRMSE% between 4.17% and 14.4% (2022/23) and 5.26% to 14.6% (2023/24). Overall, these metrics demonstrate that the DSSAT–CERES Wheat model reliably predicts phenology, growth, and yield responses to nitrogen and irrigation management in central Ethiopia. However, accurate calibration and extensive local data are crucial for optimal model performance. Gathering field, climate, and soil data is essential for effective application across Ethiopia.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Data availability statement

Data will be made available upon request.

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