



**NITROGEN USE EFFICIENCY, GRAIN YIELD AND QUALITY IN
DURUM WHEAT (*Triticum turgidum L. Var. Durum*) UNDER
IRRIGATED AND RAIN-FED ENVIRONMENTS IN CENTRAL
ETHIOPIA**

PhD DISSERTATION

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**AUGUST 2024
HARAMAYA UNIVERSITY, HARAMAYA**

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DURUM WHEAT (*Triticum turgidum L. Var. Durum*) UNDER
IRRIGATED AND RAIN-FED ENVIRONMENTS IN CENTRAL
ETHIOPIA**

**A Thesis Submitted to the Postgraduate Program Directorate
School of Plant Sciences**

HARAMAYA UNIVERSITY

**In Partial Fulfillment of the Requirements for the Degree of
DOCTOR OF PHILOSOPHY IN AGRONOMY**

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August 2024

Haramaya University, Haramay

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We hereby certify that we have read and evaluated this Dissertation entitled “Nitrogen Use Efficiency, Grain Yield and Quality in Durum Wheat (*Triticum turgidum L. Var. Durum*) Under Irrigated and Rain-Fed Conditions in Central Ethiopia” prepared under our guidance by Firew Gebremariam Woldgioregis. We recommend that it be submitted as fulfilling the dissertation requirement.

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Final approval and acceptance of the Dissertation is contingent upon the submission of its final copy to the Council of Graduate Studies (CGS) through the Candidate’s School Graduate Committee (SGC).

DEDICATION

This Dissertation is dedicated to my family and durum wheat farmers of Ethiopia.

STATEMENT OF THE AUTHOR

By my signature below, I declare and affirm that this dissertation is my own work. I have adhered to all ethical and technical principles of scholarship while conducting studies, collecting data, analyzing data, and compiling this dissertation. Any scholarly material included in the dissertation has been properly acknowledged through citations.

This dissertation has been submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy in Agronomy at Haramaya University. The dissertation is deposited in the Haramaya University Library and is made available to borrowers in accordance with the library's rules. I solemnly declare that this dissertation has not been submitted to any other institution for the award of any academic degree, diploma, or certificate anywhere.

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BIOGRAPHICAL SKETCH

The author was born on June 26, 1989, in the Assella District of the Arsi Zone in the Oromia Regional State, which is located 175 km southeast of Addis Ababa. He began his elementary education at Kulumssa Elementary School in Tiyo Woreda. He completed his secondary education at Dira Senior Secondary School in the Arsi Zone, Hitosa Woreda, from 2004 to 2005. He then attended Huruta Preparatory School in Hitosa Woreda from 2006 to 2007. Subsequently, he enrolled at Haramaya University College of Agriculture and Environmental Sciences to pursue a Bachelor of Science degree in Plant Sciences, graduating in 2010. He began his professional career in 2012 as a Technical Assistant at Haramaya University. In June 2012, he joined the College of Agriculture and Environmental Sciences and earned a Master of Science degree in Agronomy in February 2014. Immediately after graduation, he was promoted to Lecturer and Researcher at Haramaya University, where he served for four years. In the 2018/19 academic year, he received an award from the Ministry of Education for postgraduate study and returned to Haramaya University to pursue a Doctor of Philosophy degree in Agronomy.

ACKNOWLEDGEMENTS

I want to begin by expressing my deep gratitude to "Almighty God and His Mother" for my recovery from significant challenges, which reinforces my belief that with divine support, all things can be accomplished.

I sincerely thank Dr. Kindie Tesfaye, Chairman of the Advisory Committee, for his exceptional support throughout my project, from proposal to completion. His insights and connections greatly aided my field experiments. I also appreciate Dr. Tesfaye Balemi for his help in data collection and Dr. Alemz Meseret for her contributions to modeling techniques. Additionally, I am grateful to Dr. Negash Geleta for his supervision during my four years in Debre Zeit and to Dr. Abdultif Ahmed for his guidance and financial support, which were vital to our research success.

I would like to express my gratitude to Prof. Wassu Mohammed, Prof. Nigussie Dechassa, and Dr. Bulti Tesso for their essential guidance in data analysis and interpretation. I also appreciate Dr. Diego Pequeno from CIMMYT for his help with model calibration and evaluation, along with my instructors and supporters for their invaluable contributions.

I sincerely thank the Debre Zeit Agricultural Research Center for its support during my field research. I also acknowledge the School of Plant Sciences and the Directorate of Postgraduate Programs at Haramaya University for their vital resources. My gratitude extends to the Finance and Human Resources staff, particularly Tsedale Dembalashi, Bizuwork Tafes, Mekonnen Sime, and Zelalem Gitachew, for their assistance in Debre Zeit.

I sincerely appreciate Prof. Mashilla Dejene, Mr. Amare Kebede, and my colleagues Dr. Amare Fufa, Dr. Tefera Teshome, Dr. Alemayeh Dangia, and others for their invaluable support during my studies. I also thank the Kulumssa Agricultural Research Center, CIMMYT, and Haramaya University for their assistance.

Lastly, I extend my heartfelt gratitude to my family and relatives, including Cherenet Assefa, Azeze Shiferaw Assefa, Fetlewerk Assefa, Gitachew Assefa, Tirowerk Assefa, Arsima Ameha, Abedulkader Useman, Jemal Mohamed, Semira Aleyi, and Ayenalem Tineker all my relatives and friends for their unwavering support throughout my academic journey.

ACRONYMS AND ABBREVIATIONS

AACC	American Association of Cereal Chemists
BCR	Benefit-Cost Ratio
CEC	Cation Exchange Capacity
CERES	Crop Environment Resource Synthesis
CFIA	Canadian Food Inspection Agency
CIMMYT	International Maize and Wheat Improvement Center
CSA	Central Statistical Agency
CROPWAT	Calculation of crop water requirements based on soil, climate and crop.
CUL	Cultivar file
CV	Coefficient of Variation
CSP	Community Seed Production
d	Indexes of Agreement
DMRT	Duncan's Multiple Range test
DSSAT	Decision Support System for Agro-technology Transfer
DWPE	Durum Wheat Production Efficiency
DZARC	Debre Zeit Agricultural Research Center
EC	Emulsifiable Concentrate
ED	Error Differences
EIAR	Ethiopian Institute Agricultural Research
FAO	The Food and Agriculture Organization
GAIN	Global Agricultural Information Network
GLUE	Generalized Likelihood Uncertainty Estimation
HU	Haramaya University
ICS	Incident Command System
LSD	Least Significant Difference
MRR	Marginal Rate of Return
NRMSE	Normalized Root-Mean Square Error
P	Percent Level of Significance
R ²	Coefficient of Determination
RCBD	Randomized Complete Block Design
RMSE	Root-Mean Square Error
SARC	Sinana Agricultural Research Center

SD	Standard Deviation
SDS	Sodium Dodecyl Sulfate Sedimentation
SRAD	Solar Radiation
UK	United Kingdom
USA	United State of America

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3. Effect of Nitrogen Fertilizer Rates and Irrigation Intervals on yield, grain quality and Nitrogen Use Efficiency of Durum Wheat (*Triticum turgidum*L.) at Debre Zeit, Central Ethiopia (Unpublished).
4. Calibration and Evaluation of the DSSAT-CERES-Wheat Model for Simulating Growth and Yield of Durum Wheat (*Triticum turgidum* L.) Cultivars under Irrigated Environment in Central Ethiopia (Unpublished).
5. Simulation of Durum Wheat (*Triticum turgidum* L.) Growth and Yield as Influenced by Nitrogen Rates and Irrigated Intervals in Central Ethiopia (Unpublished).

NITROGEN USE EFFICIENCY, GRAIN YIELD AND QUALITY IN DURUM WHEAT (*Triticum turgidum* L. Var. *Durum*) UNDER IRRIGATED AND RAIN-FED ENVIRONMENTS IN CENTRAL ETHIOPIA

ABSTRACT

Wheat has historically been cultivated in Ethiopia using rain-fed agricultural system. However, the practice of irrigated wheat production is a relatively recent development in the country. Despite this shift, there has been a notable lack of research on the recommended improved cultivars, nitrogen application rates, and irrigation frequencies specifically for durum wheat in irrigated systems. Furthermore, the comparative benefits of irrigated versus rain-fed production systems concerning durum wheat grain yield and quality have not been extensively explored. To address these gaps, a series of studies were conducted at the Debre Zeit Agricultural Research Center in Central Ethiopia. The primary objectives of these studies were to assess the performance of durum wheat cultivars under both irrigated and rain-fed production systems, to optimize recommended nitrogen rates for durum wheat production and grain quality within rain-fed systems, to establish nitrogen fertilizer rates and irrigation frequencies for improved durum wheat production and grain quality, to calibrate and validate the DSSAT-CERES-Wheat model for simulating the growth and yield of selected durum wheat cultivars under irrigation, and to evaluate the responsiveness of durum wheat growth and yield to varying nitrogen rates and irrigation frequencies using this model. The first experiment's findings revealed that the combined analysis of variance over multiple years indicated that the cultivars significantly influenced both the yield and grain quality of durum wheat in irrigated and rain-fed systems. In the irrigated environment, the cultivars Tesfaye, Mangudo, Utuba, Tate, and Hitosa achieved the highest grain yields. Conversely, the highest protein content was found in the Bakalcha, Toltu, Bullalla, Fetan and Utuba cultivars. In the rain-fed system, the cultivars Mangudo, Tesfaye, Utuba, Hitosa, and Tate produced the greatest grain yields, while Bakalcha, Toltu, Bullalla, Feta and Utuba demonstrated elevated grain protein content. A pair-wise T-test analysis further illustrated that the irrigated system enhanced grain yield, biomass yield, thousand kernel weight, and hectoliter weight by 40.9%, 36%, 25%, and 39%, respectively, when compared to the rain-fed system. However, the rain-fed system exhibited superior values in protein content, gluten content, gluten index, and SDS-sedimentation of durum wheat, relative to the irrigated system. The second experiment focused on the impact of nitrogen rates on durum wheat cultivars. The combined data analysis indicated that varying nitrogen fertilizer rates

significantly influenced both the grain yield and quality of the cultivars. In the rain-fed production system, increasing nitrogen rates from 0 to 138 kg N ha⁻¹ led to improvements across all measured parameters. The cost-benefit analysis indicated that a nitrogen application rate of 92 kg N ha⁻¹ is optimal for durum wheat production within the study area and similar agro-climatic conditions. The third experiment examined the interaction between nitrogen rates and irrigation intervals on durum wheat. Results showed that the interaction significantly affected both grain yield and quality. Application rates of nitrogen from 0 to 138 kg N ha⁻¹ improved all studied parameters across all irrigation intervals. Notably, the highest average grain yield (6.9 t ha⁻¹) and biomass yield (16.35 t ha⁻¹) over two years were achieved with the application of 138 kg N ha⁻¹ at the II irrigation interval. The cost-benefit analysis reiterated that a nitrogen application of 138 kg N ha⁻¹ is the recommended rate for durum wheat in irrigated systems in the study area and similar agro-climatic regions. In the fourth experiment, the calibration and evaluation of the DSSAT- model for durum wheat cultivars in an irrigated environment were conducted. This involved calibrating the model with data from two years of field experiments (2018/19 and 2019/20) and evaluating it with data from three additional years (2020/21, 2021/22, and 2022/23). The results indicated that the normalized root mean square error (NRMSE) of the model ranged from 1.4 to 4.6 days for physiological maturity and from 5.4 to 9.3 kg ha⁻¹ for grain yield, among other parameters. These findings demonstrate that the model was successfully calibrated and validated for durum wheat in central Ethiopia. The fifth experiment involved utilizing the DSSAT v4.7.5 model to simulate durum wheat yield under varying nitrogen rates and irrigation intervals in central Ethiopia. The evaluation incorporated nitrogen rates of 0, 46, 92, 138, and 184 kg ha⁻¹ and three irrigation intervals (Irrigation-1, Irrigation-2, and Irrigation-3). The evaluation results indicated a strong correlation between the simulated and observed data, with percent NRMSE values ranging from 0.25 to 10%, 1.05 to 14%, and 1.65 to 23.01% under the respective irrigation intervals. Additional metrics, such as error differences (ED) and indexes of agreement (d-stat), further validated the model's performance. In conclusion, the DSSAT model has shown significant promise in accurately simulating durum wheat yield in Central Ethiopia, providing valuable insights into the potential impacts of various management practices and climate variations on durum wheat production.

Keywords: DSSAT model, Durum wheat, Irrigation, Quality, Rain-fed, Yield

1 GENERAL INTRODUCTION

1.1 Origin and Production States of Durum Wheat

Wheat (*Triticum* Ssp.) is one of the food security crops in the world's population (FAO, 2021). Durum wheat (*Triticum turgidum* var. *durum*) is one of the crops that was domesticated firstly and the origin of this crop from the Levant Region of the Near East and in the Highlands of Ethiopian about 10,000 years ago (Amadou *et al.*, 2019). In the world, 217 million hectares of wheat was cultivated annually (Erenstein *et al.*, 2022). Of the total wheat production areas in the world, durum wheat production accounts for only 8%, and 75% of it was cultivated in the Mediterranean regions (Ceglar *et al.*, 2021). In Ethiopia, both durum and bread wheat was cultivated through rain-fed production systems (Wuletaw *et al.*, 2022), and from the total wheat cultivated areas of 1,605,654 only 561,979 hectares of land were covered by durum wheat (Abate and Walelign, 2023) means approximately 0.6 million hectares. Durum wheat production accounts for 5% to 10% and bread wheat production also shares 50 to 80% of the total wheat cultivated land in Ethiopia, (Biggeri *et al.*, 2018). In the world the average yield of durum wheat ranges between 1.8 t ha⁻¹ to 6.74 t ha⁻¹ (Beres *et al.*, 2020). However, the national average yield of durum wheat was lower than 2.2 t ha⁻¹ (Mekuria *et al.*, 2018) in Ethiopia, and in the studied area average grain yield of this crop ranges between 2.92 t ha⁻¹ to 3.85 t ha⁻¹ (Truayinet and Mohammed, 2022).

1.2. Agro-ecological Requirement of Durum Wheat

Durum wheat is grown in a wide range of environments in the World from high-rainfall areas to arid and semi-arid regions where frequent drought and fluctuation of rainfall occurs (Ceglar *et al.*, 2021). However, it is more adapted to the Mediterranean type of climates, which has low and/or variable rainfall environments, with repeated terminal high-temperature stress (Vita and Taranto, 2019; Mohammadi and Haghparast, 2022). Durum wheat in Ethiopia was mainly grown in central, northwestern, and northeastern parts and it is traditionally grown by smallholder farmers on the heavy black clay soils of the highlands at altitudes ranging between the 1800 and 2800 m above sea level and Rain-Fall distribution varying from 600 to 1200 mm per annum (Alemayehu *et al.*, 2019). In addition, this crop also grown in the highlands of Oromia and Amhara region at the altitude ranges between 1800

and 2800 m above sea level and specifically, it is cultivated in the East Shewa, North Shewa, Bale, Arsi, and East Gojam zones (Truayinet and Mohammed, 2022).

1.3. Economic Importance and Utilization of Durum Wheat

Durum wheat is a *tetraploid* species cultivated widely in the World next to *hexaploid* wheat (Amadou *et al.*, 2019; Yang *et al.*, 2022) and it is one of the crops which have significant function in alleviate the food and nutritional security problems in various countries in the World (Zingale *et al.*, 2023). It is high in protein, calories and minerals such as calcium, iron, magnesium, phosphorus, potassium, zinc, and copper is much higher than the bread wheat and rice crops (Mohammadi and Haghparast, 2022). It is broadly used in a range of products, such as long and short dried pasta, fresh and sheeted pasta, couscous, bulgur and baked bread (Sissons, 2022). In Ethiopia, durum wheat is locally suitable for making *Kinche* (hard porridge), *Genfo* (porridge), *Nifro* (boiled grain) and *Kolo* (roasted grain) (Wilson, 2023).

1.4. Potential and Current Status of Irrigated Wheat in Ethiopia

Water availability and heat stress are major limiting factors to wheat yield production and they also affect the grain quality of the crops (Fahad *et al.*, 2017; Wan *et al.*, 2022). Anywhere they grow, irrigated wheat may subject to stresses that tend to restrict their growth and development which finally negatively impact on the yield (Mude, 2022). For proper growth and development, wheat needs favorable soil moisture in the root zone and extractable water capacity of soil has significant impudence on grain yield and water productivity response to irrigation (Si *et al.*, 2023; Dass *et al.*, 2024). The moisture content in the soil gradually decreases with time in dry season and simultaneously soil moisture tension increases and excessive irrigation also increases evapo-transpiration and decreases water use efficiency then reduced grain yield (Zhang *et al.*, 2019). As a result, proper using of irrigation system is acceptable strategy to increase grain yield of wheat and by solving the impact of water stress on yield and grain quality of wheat. In Ethiopia, around 5.3 million hectares of lands are suitable for irrigated agriculture through surface, ground and rainwater sources however from the total appropriate irrigable lands less than 2% of it has been used for crop production but irrigation is basic policy to reduced poverty and increased food security (Wuletaw *et al.*, 2022). In the similar manner, in Ethiopia, more than 3.8 to 6 million hectares of land are suitable for irrigation (Worqlul *et al.*, 2017) and the lowland areas of the country are the major irrigable land, that was accountedfor1.0 to 4.3 million hectares (Belachew *et al.*, 2022). Thus, irrigation development in Ethiopia is a key to sustainable and reliable

agricultural development which leads to overall development (Gebremeskel *et al.*, 2022). Currently, the Ethiopian government is heavily expanding irrigated wheat production throughout the country to minimize the inequity between providers and consumers for wheat (Gedifew, 2022) and in Ethiopia, more than 3000, 187,000 and 400,000 hectares of land has been cultivated during 2019/20, 2020/21, and 2021/22 through irrigated cultivation system, respectively with the average grain yield ranges from 4 to 7 tons per hectare (Wuletaw *et al.*, 2022). The average grain yield recorded during the 2020/21 under irrigated cultivation system was 5.47 million tons but in Egypt 9 million tons (FAO, 2021). It indicated that wheat production under irrigate production system increased the cultivated land for each year but production from the cultivated land was in still lower than the world production.

1.5. Effect of Nitrogen Fertilizer on Yield and Quality of Durum Wheat

Appropriate coordination of nitrogen fertilizer rates and irrigation regimes is important to improve yield and water use efficiency of the crops (Qi *et al.*, 2020). The variations in yield between the cultivars were related to differences in water and nitrogen use efficiencies (Boulelouah *et al.*, 2022). Nitrogen fertilizer is one of the most important actions that increases grain yield and improves grain quality in wheat production (Rekaby *et al.*, 2016). Plants need nitrogen for healthy canopy growth to intercept solar radiation effectively for photosynthesis (Luo *et al.*, 2021). On the other hand, nitrogen is essential to wheat for the production of biomass and lead to store in this biomass remobilizes later to the grain and it is estimated that up to 95% of the remobilized N is taken up prior to pre and post anthesis (Sharma *et al.*, 2023). In some instances, nitrogen is over-applied to achieve as close as possible to the grain yield potential and ensure a desirable quality of durum wheat (Sissons *et al.*, 2023). The excessive N application is not only to ensure the desired wheat quality but also to prevent wheat market price discounts (Bicego *et al.*, 2019). Grain quality parameters such as grain test weight, grain protein content, and falling number are important end-use quality indicators with marketing implication. N levels and weather conditions during reproductive phase can influence the test weight, a traditional standard grain quality measurement (Zhygunov *et al.*, 2022). Conversely, nitrogen is considered as the second most limiting factor in the crop production and limits yield in non-fertilized agriculture in globally (Govindasamy *et al.*, 2023). Therefore, it is applied in order to increase yield and improve crop quality and nitrogen fertilization contributes significantly to protein content, especially when fertilizer rates satisfy the requirements of both yield and protein formation.

Durum wheat grain protein functionality can be influenced by nitrogen fertilization, particularly in the varieties of relatively with less gluten strength (Zingale *et al.*, 2023). Nitrogen fertilization management offers the opportunity for increasing wheat grain protein content and other related quality traits. According to Melash and Ábrahám (2022) report, grain protein content is a function of total nitrogen uptake and of the partitioning of nitrogen and dry matter to the grain. Durum wheat protein content consistently lower than 12% or starch content “yellow bean” kernels higher than 20% is an indication that a wheat producer needs to use more N fertilizer or better manage the N being applied (Gerba *et al.*, 2013). Suitable durum wheat grain features for pasta and macaroni products are amber (yellow) color, vitreous endosperm, hardest grain texture and unique combination of grain protein that favors good pasta cooking quality (Saini *et al.*, 2023).

In Ethiopia around 12.6 million hectares of land was a Vertisols and of the total 7.6 million hectares was found in the highlands part of the country (Fresew *et al.*, 2018). Durum wheat in Ethiopia is mainly grown on heavy black clay soils (Vertisols) of highlands and Vertisols in Ethiopia and other part of Africa generally have soil pH ranging between 7.5 and 8.5 in the soil profile (Assefa, 2018). High pH content of the Vertisols favors gaseous loss of ammonia when urea or ammonium fertilizers are applied to the surface (Assefa and Adhiena, 2021). As a result, durum wheat is mostly successful in soils with pH 6 in CaCl₂ (Gerba *et al.*, 2013). On the other hand, reports, the low infiltration rates of Vertisols could also create environment favorable for de-nitrification since O₂ diffusion rate in water is very low and Nitrogen deficiency is a common problem in cool, wet areas, such as in highland Vertisols (Amare, 2015). Therefore, draining nitrogen fertilization to durum wheat is very important to mitigate the risk of N losses and to improve the quality of grain.

Irrigation of wheat is an acceptable strategy to increase grain yield and crop returns where this is economically viable (Chawla and Balasaheb, 2023). However, the response of wheat cultivars to nitrogen uptake and lost was influenced by irrigation regime (Tan *et al.*, 2021). Even though, irrigation of wheat generally leads to an increase in biomass and grain yield but had no impact on harvest index and grain quality (Walsh *et al.*, 2020; Si *et al.*, 2023) whereas Sheng *et al.* (2022) reported that water-saving irrigation is playing important roles in ensuring food security, and improving wheat quality. Usually the kernels become larger with irrigation than rainfed farming, and this causes a dilution of grain protein and yellow pigment and an increase in yellow berry which is associated with lower semolina extraction (Singh and Jain, 2000). This can be corrected by increasing N application at sowing, and especially by

splitting application between stem elongations and heading more N translates into more grain protein, thereby reducing yellow berry incidence, which is inversely related to grain protein content (Sissons *et al.*, 2014).

Nitrogen is essential for both optimum yield and grain protein content of durum wheat (Ayadi *et al.*, 2022), and its applications are required where nitrogen is deficient in the soil or with irrigation when high grain yield and protein are desired (Wang *et al.*, 2010; Zhang *et al.*, 2021). In rice and wheat crops the nitrogen requirements increase with increasing moisture availability the nitrogen allows more photosynthesis by increasing the leaf area index and number of grains per spikelet (Tanaka *et al.*, 2022). Increases nitrogen rate grain protein content, gluten content, carotenoids, and the dough strength as assessed by sodium dodecyl sulfate (SDS) sedimentation (Zingale *et al.*, 2023). However, the interaction between the effects of the amount and timing of nitrogen on yield and grain protein can vary with environmental conditions and different genotypes (Marinho *et al.*, 2022). Applying nitrogen fertilizer and other management practices increased the yield of wheat but in some cases, these show adverse effects due to severely limiting irrigation (Wu *et al.*, 2019; Derara *et al.*, 2024).

1.6. Impact of Irrigation on Yield and Grain Quality of Durum Wheat

Irrigation is the main driver for crop production in many agricultural regions across the world and it plays an essential role in agricultural production and water management in the production of crops (Dari *et al.*, 2023; Gamal *et al.*, 2023). Irrigation production system increases the capacity of land to produce crop per cropping season (Riessen and Palarca, 2021). In addition, irrigation also indirectly promotes crop commercialization by incentivizing farmers to diversify their production system (Rajkhowa, 2024). Irrigation production system significantly affected Durum wheat production and grain quality. For instance, 12.5% deficit in irrigation led to 45% grain yield reduction of durum wheat (Sanyal *et al.*, 2024). On the other hand, Mohammadi (2024) reported that supplemental irrigation was significantly increased grain yield at the range of 18.7% – 45.8% depending on the genetic viabilities of durum wheat cultivars. The grain yields of durum wheat 5.21 t ha⁻¹ and 5.55 t ha⁻¹ were obtained by surface irrigation and drip irrigation, respectively (Çetin *et al.*, 2022). On the other hand, supplemental irrigation decreased the grain protein content and wet gluten content but an increase in starch content (Demirel *et al.*, 2023). Sissons *et al.* (2014)

also reported that high-input irrigation systems increased the good milling and pasta-making quality of durum wheat.

1.7. DSSAT-Crop Model on Prediction of Wheat Production

The Decision Support System for Agro-technology Transfer (DSSAT) is a software application program that comprises crop simulation models for over 42 crops (Boote, 2020; Wajid *et al.*, 2021). The crop simulation models simulate growth, development and yield as a function of the soil-plant-atmosphere dynamics (Wu *et al.*, 2013). Crop models such as DSSAT have been used extensively to predict yield response to various crops including wheat different climatic scenario (Waffa and Benoit, 2015) and DSSAT model also facilitate researchers' ability to understand and interpret experimental results, and to diagnose yield gaps (Liu *et al.*, 2017). Growth, development and grain yield of wheat was evaluated through DSSAT in different environmental conditions (Dwivedi *et al.*, 2022; Ajilogba and Walker, 2023).

1.8. Rationale of the Study

Durum wheat has been cultivated in Ethiopia for many years, and the country is considered the center of origin for this crop (Abate and Walelign, 2023). This crop is one of the essential self-sufficiency crops produced in the country, providing nutritional and economic advantages to small-scale farmers while also serving as a raw material for other processed food manufacturing in the industry. However, the production of both bread and durum wheat is insufficient, covering only about 75% of consumer demand in Ethiopia. As a result, approximately 25% of wheat grain is imported from outside the country to meet consumer demand (Silva *et al.*, 2023). Consequently, the government is currently focusing on cultivating wheat under an irrigated production system to achieve food security for the population.

Regarding durum wheat production under irrigation, farmers lack sufficient information on appropriate cultivar selection, nitrogen rates for durum wheat production, and the amount of irrigation necessary for successful cultivation, particularly in the central part of Ethiopia. Although the central part of Ethiopia is one of the potential areas for durum wheat production, the farmers living in this region lack information related to durum wheat production and the grain quality variation between irrigated and rain-fed growing

environments. This situation results in farmers cultivating durum wheat solely in rain-fed conditions, leading to low average yields per hectare.

To address this issue, the Ethiopian government has initiated durum wheat production under an irrigated production system. However, to achieve the government's goals of reducing poverty and maintaining food self-sufficiency through irrigation, there is a lack of new irrigation technologies, including the selection of appropriate cultivars, nitrogen rates, and irrigation water regimes for durum wheat production in the area. Therefore, the present research was undertaken based on the following premises:

1. There is a lack of recommended cultivars used in irrigation systems, and low durum wheat grain yields under rain-fed system are attributed to the absence of improved durum wheat cultivars. Additionally, the effects of production systems on grain yield and quality of durum wheat cultivars in the study area are not evaluated. This study aims to evaluate the performance of different durum wheat cultivars under irrigated and rain-fed production systems in Central Ethiopia.
2. In the rain-fed production system, the recommended nitrogen rates have not updated for the newly improved durum wheat cultivars in the study area. Thus, this study seeks to assess the effects of nitrogen fertilizer rates on yield and grain quality of durum wheat cultivars under rain-fed conditions in Central Ethiopia.
3. There is a lack of recommended nitrogen rates and irrigation interval for irrigated durum wheat production in the area. Therefore, this study aims to evaluate the impact of nitrogen fertilizer rates and irrigation frequency on the yield and grain quality of durum wheat in Central Ethiopia.
4. In the study area, there is not use of DSSAT crop modeling for the irrigated growing environment. Thus, this research was conducted to calibrate and evaluate the model for the selected durum wheat cultivars at Debre Zeit in Central Ethiopia.
5. Finally, the application of DSSAT crop model for simulating durum wheat responses to the nitrogen rate in the irrigated growing environment is unavailable for the study area. Consequently, this research aims to utilize the DSSAT crop model to simulate

the response of durum wheat to irrigation intervals and nitrogen fertilizer rates in Central Ethiopia.

1.9. Objectives of the Study

1.9.1. General Objectives

- To assess nitrogen use efficiency, grain yield and quality of durum wheat (*Triticum turgidum* L.) under rain-fed and irrigated conditions in central Ethiopia.
- To calibrate, evaluate and apply the DSSAT crop model to simulate durum wheat production under irrigated conditions in central Ethiopia.

1.9.2. Specific Objectives

- 1) To select best performing durum wheat cultivar based on the grain yield and quality under rain-fed and irrigation systems.
- 2) To evaluate the effects of different N-fertilizer rates on N-use efficiency, grain yield and quality of selected durum wheat cultivars under rain-fed system.
- 3) To assess the effects of different N-fertilizer rates and irrigation intervals on N-use efficiency, grain yield and quality.
- 4) To calibrate, validate and evaluate of DSSAT–CERES-Wheat model to growth and yield of the selected durum wheat cultivars under irrigated growing condition in central Ethiopia.
- 5) To simulate the growth and yield of durum wheat as influenced by nitrogen fertilizer rates and irrigated frequencies in Central Ethiopia.

1.10. Research questions

- 1) Which durum wheat cultivar performs best based on grain yield and quality under rain-fed and irrigation systems?
- 2) Do different N-fertilizer rates and irrigation intervals have effects on N-use efficiency, grain yield, and quality?
- 3) Does the DSSAT crop model have an effect on simulating durum wheat production under irrigated conditions in central Ethiopia?

1.11. Description of the Study Area

The experiments were carried for four experimental years (2020 to 2024) under both rain-fed and irrigated production systems at the Debre Zeit Agricultural Research Center (DZARC), located in the Ada'a District of the Oromia Regional State, Ethiopia. The DZARC is positioned at a latitude of 8°41'36" and a longitude of 39°03'17", with an elevation of 1880 meters above sea level (Alemayehu *et al.*, 2019). This experimental site is situated in the central highlands of Ethiopia, an area well-suited for the cultivation of durum wheat. The soil at the site is heavy black soil, 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 available phosphorus level was recorded at 23.6 ppm (see Table 1.1). The average relative humidity in the area is 61.3%, and the average annual rainfall during the experimental years was 732.8 mm. Moreover, the average minimum and maximum temperatures for the study area were 7.9 °C and 26.2 °C, respectively (NMSA, 2020). Monthly rainfall, as well as the distribution of maximum and minimum temperatures during the experimental years is detailed in Table 1.2. A map of the research site is presented in Figure 1.1.

Table 1.1. Selected soil properties of the study site

Soil properties	Optimum	Methods of soil analysis	Rating
pH (H ₂ O) 1: 2.5	6.61	pH meter (H ₂ O 1: 2.5)	Agegnehu <i>et al.</i> , 2021
Available P (ppm)	23.6ppm	Olson's sodium method	Mesfin and Tekalign, 2011
Total N (%)	1%	Kjeldahl method	Alemayehu <i>et al.</i> , 2024
Organic carbon (%)	0.1%	Walkley-Black method	Hillette <i>et al.</i> , 2015
CEC (cmol(+).kg ⁻¹)	51.59	ICP- Method (Hendershot & Duquette, 1986)	Virmani <i>et al.</i> , 1982

Table 1.2. Rainfall and temperature distribution of the experimental site during the tested years (2020 to 2024)

Months	2020		2021		2022		2023		2024						
	Rainfall (mm)	Temp (T °C)		Rainfall (mm)	Temp (T °C)		Rainfall (mm)	Temp (T °C)		Rainfall (mm)	Temp (T °C)				
		Max.	Min.		Max.	Min.		Max.	Min.		Max.	Min.			
January	0	26.7	4.1	17.1	26.9	5	15	27	6.1	12	27.1	4.4	0	28	5
February	0	24.8	6.7	0	27.1	6.8	15	28	7	1.6	28.2	4	0	28.5	4
March	0	28.1	7.8	12.2	28.7	8.2	0	29.2	8	1	29.5	6	2	29	5
April	14.5	29.1	9.9	16	30.4	10.2	12	30.5	10	10	30.6	6.7	7	31	6
May	59.1	28.1	8	0	30.6	8.1	10	31.8	8.1	9	32	7.8	15	31	7.4
June	88.7	24.8	11.1	96.1	26.9	9.9	88	29	8.6	74	29.3	9.9	50	30	10
July	167.4	21.9	12.3	196.3	22.3	10.7	190	22.6	10	187	22.8	8	193	22	7
August	260.7	23.1	10.7	193.2	23.8	11.1	155	24	11.1	150	24.4	8.4	127	25	8.5
September	255.4	24.6	9.9	124.3	25.1	10.1	120	25	9.2	112	25.2	10	201	25	9.5
October	90.4	26.2	5.4	0	26.8	6	0	26.6	7.3	0	27.1	9.1	55	27.4	9
November	0	25.1	4.8	0	26.2	4.3	0	26.8	4.5	0	27	7.1	10	26.8	7
December	0	25.3	3.7	0	25.5	4	0	26	4.4	0	26.3	4.2	0	26.5	4.5

Source: Debre Zeit Agricultural Research Center Meteorological Station, 2024

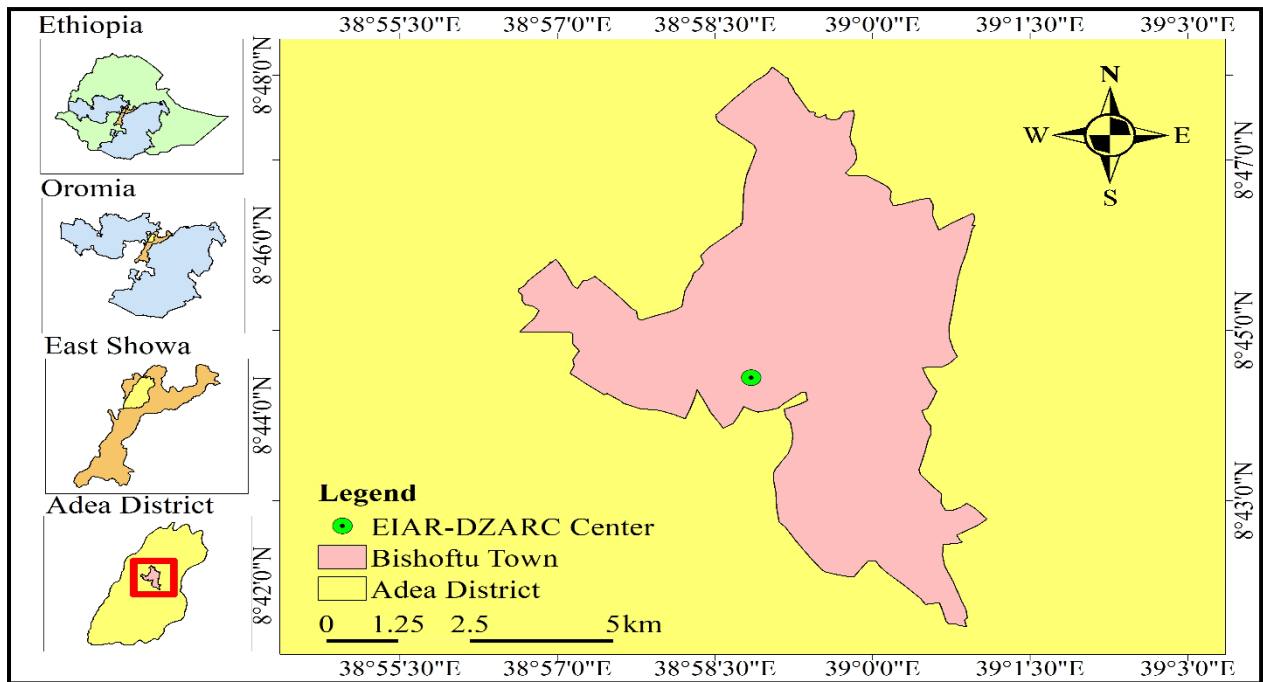


Figure 1.1. Map of the research site in East Shoa, Oromia, Ethiopia

1.12. References

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2. EVALUATION OF DURUM WHEAT (*Triticum turgidum* L.) CULTIVARS FOR GROWTH, YIELD RELATED TRAITS, YIELD, AND GRAIN QUALITY UNDER IRRIGATED AND RAIN-FED PRODUCTION SYSTEMS AT DEBRE ZEIT, CENTRAL ETHIOPIA

ABSTRACT

Wheat production under irrigation has recently become a prominent production system in Ethiopia. However, there is limited information on the comparative advantages of irrigated versus rain-fed production systems regarding the yield and grain quality of wheat. Furthermore, the performance of wheat cultivars may vary between the two production systems. The current study was conducted to evaluate the performance of durum wheat cultivars in terms of growth, yield, and grain quality under both irrigation and rain-fed production systems. The treatments in the experiments consisted of twenty durum wheat cultivars. The experiments were conducted separately under irrigated and rain-fed conditions for two consecutive years, 2020 and 2021. Each experiment was laid out in a randomized complete block design with three replications. The effects of the production systems on the tested parameters were evaluated using pair-wise T-test analysis. According to the results of the pair-wise T-test analysis, the irrigated production system resulted in increased plant height (8.5%), productive tillers per plant (45.6%), spikelets per spike (25.8%), kernels per spike (42.1%), grain yield (40.9%), biomass yield (36%), thousand-kernel weight (25%), and hectoliter weight (39%) of durum wheat compared to the rain-fed system. The combined results over the years 2020 and 2021 indicated that the tested cultivars significantly affected the grain yield and quality of durum wheat in each production system. The cultivars Mangudo, Tesfaye, Utuba, Tate, and Hitosa recorded the highest grain yields, while cultivars Bakalcha, Toltu, Bullalla, Fetan, and Utuba exhibited higher grain protein content in both production systems. The cultivar Utuba showed higher grain yield and grain protein content in both production systems. Mangudo, Tesfaye, Tate, and Hitosa could be promising cultivars for both rain-fed and irrigated systems to enhance the grain yield of durum wheat in the study area, while cultivar Utuba had higher grain yield and quality in both rain-fed and irrigated production experiments. Therefore, it is a recommended cultivar for the study area and for areas with similar agro-ecological conditions.

Key words: Agro-ecology; Grain yield; Pair-wise analysis; Production system; Quality.

2.1. INTRODUCTION

Durum wheat (*Triticum turgidum* L.) is grown in a wide range of environments around the world, from high-rainfall areas to arid and semi-arid regions where frequent droughts and fluctuations in rainfall occur (De Vita and Taranto, 2019). In Ethiopia, durum wheat is primarily cultivated in the central, northwestern, and northeastern regions. It is traditionally grown by smallholder farmers in the heavy black clay soils of the highlands at altitudes ranging from 1,800 to 2,800 meters above sea level, with rainfall distribution varying from 600 to 1,200 mm per annum (Zemedede, 2019; Kamil, 2020). Of the total wheat production area worldwide, durum wheat accounts for only 8%, with approximately 75% of it cultivated in the Mediterranean regions (Amadou *et al.*, 2019; Ceglar *et al.*, 2021). In Ethiopia, durum and bread wheat are both cultivated in rain-fed production system. Out of a total of 1,605,654 hectares cultivated for wheat, only 561,979 hectares is allocated to durum wheat (Wuletaw *et al.*, 2022).

The productivity of durum wheat in Ethiopia is less than 2.2 tons per hectare ($t\ ha^{-1}$) (Mekuria *et al.*, 2018), while productivity in the studied area ranges between $2.92\ t\ ha^{-1}$ and $3.85\ t\ ha^{-1}$ (Truayinet and Mohammed, 2022). Small- and large-scale farmers in Ethiopia focus more on bread wheat production than on durum wheat production (Biggeri *et al.*, 2018). Consequently, the Ethiopian government is importing durum wheat, which accounts for approximately 50% to 80% of the total wheat imports (Mesay, 2017). On the other hand, more than 3.8 to 6 million hectares of land in Ethiopia is suitable for irrigation (Abeyou *et al.*, 2017), and the lowland areas of the country are favorable for crop production under irrigation (Kefena *et al.*, 2023). According to Gebremeskel *et al.* (2022), irrigation development is key to sustainable and reliable agricultural development, which will contribute to the overall development of Ethiopia. In this regard, the Ethiopian government is heavily expanding irrigated wheat production across the country in an effort to minimize the imbalance between supply and demand for wheat (Gedifew, 2022). However, Over-irrigation can cause deep drainage from rising water tables that can lead to problems of irrigation salinity requiring watertable control by some form of subsurface land drainage (England, 2020).

The effect of cultivars on durum wheat production has been evaluated by various researchers, including Miesho (2014), Muez *et al.* (2015), Ashinie and Kindie (2016), Bassi and Sanchez-Garcia (2017), Mekuria *et al.* (2018), Alemayehu *et al.* (2019), Eshetie Abebe *et al.* (2020), Shibeshi and Dawit (2021), Behailu *et al.* (2022), Alemayehu *et al.* (2022), Boucheta

et al. (2023), and Shitaye *et al.* (2024), all under rain-fed production systems throughout the country. These findings indicate that evaluating improved durum wheat cultivars in different agro-climatic conditions and production systems is crucial for increasing durum wheat yields in the country. Approximately forty-two improved durum wheat cultivars have been developed by the national research system in Ethiopia; these varieties are exclusively released for the rain-fed production system across various locations. Expanding the cultivation of durum wheat through irrigated production system is essential for enhancing durum wheat yields in Ethiopia. To increase durum wheat yield under irrigation, suitable and feasible cultivars are required. However, suitable cultivars for the irrigated production system are currently not identified in Ethiopia. Therefore, evaluating potential durum wheat cultivars under both irrigated and rain-fed production systems is important. This research was conducted with the following objectives:

- i) To select promising durum wheat cultivar(s) with better yield and grain quality under rain-fed and irrigated production systems.

2.2. MATERIALS AND METHODS

2.2.1. Description of the Study Area

Please refer the description of the study area from subsection 1.11 (Page 32).

2.2.2. Experimental Materials

Twenty improved durum wheat cultivars were evaluated under rain-fed and irrigated production systems in separate research experiments conducted at the Debre Zeit Agricultural Research Center. The planting materials were released between 2002 and 2017 by the Debre Zeit Agricultural Research Center (DZARC) and the Sinana Agricultural Research Center (SARC). The grain yield potential of the cultivars ranged from 2,780 to 7,630 kg ha⁻¹. A list and description of the cultivars are presented in Table 2.1.

Table 1.1. Description of durum wheat cultivars used in the study

S/N	Cultivar	Year of release	Altitude (m above sea level)	Yield (kg ha ⁻¹)	Maintaining centers
1	<i>Alemtena</i>	2016	1600–2200	3000–5000	DZARC
2	<i>Bakalcha</i>	2005	2000–2500	3200–6700	SARC
3	<i>Bullalla</i>	2017	2000–2500	3950–7630	SARC
4	<i>Denbi</i>	2009	1800–2800	4000–5600	DZARC
5	<i>Dire</i>	2012	2000–2500	4900–5200	SARC
6	<i>Donmateo</i>	2017	1800–2650	4000–5500	DZARC
7	<i>Ejersa</i>	2005	2000–2500	3200–6200	SARC
8	<i>Fetan</i>	2017	1600–2200	3000–5000	SARC
9	<i>Gerardo</i>	1976	1800–2500	2000–3000	DZARC
10	<i>Hitosa</i>	2009	1800–2650	4000–6000	DZARC
11	<i>Mangudo</i>	2012	1800–2650	3500–6000	SARC
12	<i>Mokiye</i>	2012	450–1200	3500–5600	DZARC
13	<i>Obsa</i>	2006	2000–2500	4000–6000	SARC
14	<i>Tate</i>	2009	2000–2500	4200–5900	SARC
15	<i>Tesfaye</i>	2017	1800–2800	5000–5500	DZARC
16	<i>Toltu</i>	2010	2000–2500	4400–6000	SARC
17	<i>Ude</i>	2002	1800–2650	3000–5500	DZARC
18	<i>Utuba</i>	2015	1800–2650	4000–6500	DZARC
19	<i>Werer</i>	2009	450–1200	4000–4500	DZARC
20	<i>Yerer</i>	2002	1800–2650	3000–5000	DZARC

DZARC = Debre Zeit Agricultural Research Center and SARC = Sinana Agricultural Research Center. Ministry of Agriculture and livestock resource crop variety register issue no.20

2.2.3. Treatments and Experimental Design

The rain-fed and irrigated experiments included twenty durum wheat cultivars arranged in a randomized complete block design (Table 2.1). The rain-fed experiment occurred during the main cropping seasons on July 20, 2020, and July 18, 2021, while the irrigated experiment took place in the off-cropping seasons on November 16, 2020, and November 16, 2021. Plot sizes were 3 m x 2 m (6 m²) for rain-fed and 5 m x 4 m (20 m²) for irrigated systems. Spacing between plots was 0.5 m and 1 m for rain-fed, and 1.5 m and 2.5 m for irrigated, with each cultivar randomly assigned to plots.

2.2.4. Experimental Procedures

In both rain-fed and irrigated production systems, experimental lands were plowed with a tractor and plots prepared manually. Improved durum wheat seeds were planted at 125 kg per hectare using a hand drill at a depth of 10 cm with the space of 20 cm, covered with soil. Seeds were sown on July 20, 2020, and July 18, 2021, for rain-fed, while under irrigated conditions, they were sown on November 16, 2020, and November 16, 2021.

In both systems, the recommended NPS fertilizer (100 kg ha⁻¹) was applied by banding at sowing, while urea (200 kg ha⁻¹) was applied in two splits: two-thirds at tiller initiation and one-third at the booting stage. Irrigation was provided based on FAO 56 guidelines, with water applied when 55% of water at 1–1.5 m depth was depleted, using furrow irrigation. A total of 585.4 mm of irrigation water was applied, intervals with CROPWAT software V-8.

Weed control was achieved through hand weeding, and in the rain-fed system, stem and leaf rust were managed with Tilt 250 EC at 0.5 L per hectare. Harvesting was done manually in both systems.

Table 2.2. Irrigation water applied to the crop during 2020 and 2021 cropping seasons.

Irrigation frequency	Amount of water applied after planting (mm)
November 16	22.8
November 26	23
December 6	31
December 16	34
December 26	36
Janaury 5	47
Janaury 15	47.5
Janaury 25	49
February 4	56.4
February 14	56
February 24	49.7
March 6	49
March 16	48
March 25	36
Total	585.4

Source = soil and weather data from Debre Zeit Research Center, and all other required data form FAO 56.

2.2.5. Data Collection and Measurements

2.2.5.1. Phenology and plant growth parameters

Population density per meter square: Population density was recorded when the plants fully covered the ground in each plot. A quadrant (1 m²) was used to count the number of seedlings within the area of the quadrant.

Number of productive tillers per plant: The number of productive tillers was counted from ten randomly selected plants grown in an area of 0.1 m² (0.5 m length by 0.2 m width) located in the middle rows of the plot, and then the total was divided by ten.

Days to heading: Days to heading were determined by counting the number of days from the planting date to when 90% of the heads were formed.

Days to physiological maturity: Days to physiological maturity were determined by counting the number of days from the planting date to the date when the crop appeared to reach physiological maturity, indicated by a yellowish color of the straw.

Plant height (cm): Plant height was recorded from ten randomly selected plants in the middle rows of each plot and then averaged by dividing the total height by ten at physiological maturity of the crop.

2.2.5.2. Yield and yield related parameters

Number of spikelets per spike: The number of spikelets per spike was counted from the main spike of ten randomly selected plants from the two middle rows at maturity, and the average was recorded.

Number of kernels per spike: The number of kernels per spike was also recorded from the main spike of ten randomly selected plants from the two middle rows, and the average was calculated.

Grain yield (kg ha^{-1}): Grain yield was obtained by threshing the plants used for biomass yield estimation. The grain from each plot was measured in grams using a sensitive balance, and the data was recorded after adjusting the grain weight to 12.5% moisture content. Subsequently, the grain yield per plot was expressed as kilograms per hectare.

Biomass yield (kg ha^{-1}): The biomass harvested from the four middle rows of each experimental plot was weighed after drying for 72 hours under the sun. The results were then converted into kilograms per hectare.

Straw yield (kg ha^{-1}): Straw yield was calculated by subtracting the grain yield from the total harvested biomass yield per plot and then converting it into kilograms per hectare.

Harvest index (%): The harvest index was estimated by dividing the grain yield by the biological yield per plot and then multiplying by 100.

$$\text{HI (\%)} = \text{Grain yield (kg ha}^{-1}\text{)} / \text{biological yield (kg ha}^{-1}\text{)} \times 100$$

2.2.5.3. Grain quality parameters

Thousand kernel weight (g): Grain samples were collected, and 1,000 seeds were counted using an electric seed counter. The counted seeds were then weighed using an electronically sensitive balance at seed moisture reached at 12.5% seed moisture content.

Hectoliter weight (kg/hl): The one kilogram of sample seeds was taken from the experimental plot to evaluate the hectoliter weight of the seed. The hectoliter weight of grain was determined using a seed Buro hectoliter mass device and an electronic balance at a 12.50% seed moisture content. The results were reported in kilograms per hectoliter.

Starch content (%): The 15 g of sample seeds were collected from the tested plot to test starch content of the seed. Starch content was tested by diluting the samples with water (300 µL sample + 700 µL Milli-Q water) and measured using ionic chromatography (ICS-3000, Thermo Scientific Dionex, USA). The pellet was used to determine the starch content.

Protein content (%): The nitrogen content of the grain was determined using the micro-Kjeldahl method, as stated in AACC method 46-11. The nitrogen content was then converted to percent protein by multiplying it by a factor of 6.25. Urea was used as a control.

Wet gluten content (%): Wet gluten content was recorded according to the AACC (2000) Method 38-10 hand washing method. This method involved using a 2% sodium chloride solution for washing. During the washing process, starch, water-soluble pentoses, water, and dilute salt-soluble proteins were washed out. The gluten was then press-dried between the hands and rolled into a ball. The remaining mass was determined and recorded as the wet gluten content of the sample.

Dry gluten content (%): Dry gluten content was obtained from the total wet gluten by drying it at 150°C and weighing it after four minutes in an air-draft oven to get the dried gluten mass.

Gluten index (%): Gluten index was determined using the automatic Glutomatic system (Perten, 1990; Perten Instrument AB, Huddinge, Sweden). After hand washing, the gluten ball was gently placed in the gluten index sieve cassette (88 µm screen). Following centrifugation at 6000 rpm for 1 minute, the gluten index sieve cassette was removed, and the weight of the gluten portion that passed through was measured to the nearest 0.01 g. The percentage of gluten index was calculated as follows:

$$\text{Gluten index (\%)} = \text{Gluten remaining on the sieve (g)} / \text{Total gluten} \times 100$$

Sodium dodecyl sulfate sedimentation volume (ml): This was recorded as described in the AACC Method No. 56-70 (2000) by measuring the SDS sedimentation volume increase for a batch of eight samples using a hand mixing procedure with 3% SDS-lactic acid as a reagent. The sedimentation volume was recorded to the nearest 0.5 ml after 20 minutes at room temperature. The results were expressed as the height (ml) of the interface line between the solid (ground sample) and the liquid in a measuring cylinder.

2.2.6. Data Analysis

The analysis of the variance between rain-fed and irrigated production systems was conducted following the statistical analysis procedure described by Gomez and Gomez (1984), and was performed separately using GenStat statistical software version 19. The Bartlett test was employed to assess the homogeneity of variance between production years within each production system. The combined analysis of variance across the years within the production system was carried out using GenStat statistical software version 19. Mean separation was performed using Duncan's multiple range test (DMRT) at a significance level of $p \leq 0.05$. Additionally, the effects of production systems on the crop phenology, growth, yield, and grain quality parameters of durum wheat cultivars were evaluated through pairwise T-test analysis, as indicated by Soriano *et al.* (2016).

2.3. RESULTS AND DISCUSSION

2.3.1. Phenological Response of Durum Wheat Cultivars to Irrigated and Rain-fed Production Systems.

2.3.1.1. Phenological parameters

Number of days to emergence

The combined data analysis of variance over the two years showed that the cultivar had a significant difference ($p \leq 0.01$) at the number of days to emergence of durum wheat under irrigated and rain fed production system. The cropping year, as well as the combined effect of cropping years with cultivar, did not affect the number of days to emergence under both production systems at $p > 0.05$ (Table 2.3).

In the rain-fed system, the days to emergence ranged from 6.5 to 10 days (Table 2.4). The seeds of the cultivar *Tesfaye* emerged later, while the cultivars *Dire*, *Donmateo*, *Fetan*, *Obsa*, and *Ude* emerged relatively early (Table 2.4). In the irrigated production system, the number of days to emergence for durum wheat cultivars ranged from 5 to 7 days (Table 2.4). In this system, the cultivars *Bakalcha*, *Hitosa*, *Mangudo*, *Tate*, and *Tesfaye* emerged later, while the cultivars *Fetan*, *Gerardo*, *Toltu*, and *Ude* emerged relatively early. These separate research results indicate that the number of days to emergence was significantly different among the cultivars in both rain-fed and irrigated production systems. Days to emergence and seedling development are influenced by the genetic factors of the cultivars (Horváth *et al.*, 2023).

The results of the pairwise T-test on the combined data over the years indicated that the irrigated production system reduced the number of days required for seed emergence of durum wheat cultivars compared to the rain-fed production system by 20.5% (Table 2.5). These variations are clearly associated with higher temperatures and adequate soil moisture during the irrigation season, which accelerate germination and seedling development (Table 1.2). An increase in temperature by 1°C enhances enzymatic activities, resulting in accelerated germination and seedling development of wheat (Sharma *et al.*, 2022). Previous research has also indicated that environmental factors affect the germination and seedling emergence of wheat crop by 11% and 25%, respectively (Adeli *et al.*, 2022). Wu *et al.* (2012) reported that higher soil moisture and lower temperatures decreased the emergence time by 3

to 4 days compared to low moisture and high temperatures, which are common in irrigated production systems.

Days to 90% heading

The combined data analysis of variance over the two years showed that, under both irrigated and rain-fed production systems, cultivar significantly affected ($p \leq 0.01$) the number of days to 90% heading in durum wheat. The year and the combined effect of years with cultivar did not ($p > 0.05$) influence this parameter in either production system (Table 2.3).

Under the irrigated production system, the cultivar *Obsa* recorded the maximum number of days to heading, while the *Donmateo* and *Werer* cultivars recorded the minimum number of days to heading, both were significantly different at $p \leq 0.01$ (Table 2.4). Conversely, in the rain-fed production system, the number of days to heading ranged from 56 to 65 days. The highest number of days to heading was recorded for the *Bakalcha*, *Dire*, *Ejersa*, and *Toltu* cultivars, while the *Donmateo* cultivar had the smallest number of days to heading, also were significantly different at $p \leq 0.01$ (Table 2.4). The results of the current research indicated that, in both rain-fed and irrigated production systems, the number of days to heading was significantly different among the cultivars. These results could be attributed to the genetic variation among the cultivars.

The pairwise T-test indicated that, in the irrigated production system, the number of days to 90% heading decreased by 2 days compared to the rain-fed production system (Table 1.1). Conversely, the rain-fed production system resulted in a 3.5% increase in the number of days to heading compared to the irrigated production system (Table 2.5). The variations in days to heading between the production systems were due to climatic variability. For instance, under the rain-fed production system, the average temperature and rainfall recorded were 24 °C and 143.1 mm, respectively, while under the irrigated production system, the average values for temperature and soil moisture were 26.05 °C and 102.4 mm, respectively (Table 1.2). This variation led to a reduction in the number of days to heading in the irrigated system. Previous research has also indicated that the number of days to heading decreases by 5% under high temperature and low soil moisture content which is compared to high soil moisture content and low temperatures (Chowdhury *et al.*, 2021; Majer *et al.*, 2023).

Table 2.3. Mean square value for phenological parameters of durum wheat cultivars under rain-fed and irrigated production systems (data combined over the 2020 and 2021 cropping years).

Source of variation	DF	Rain-fed production system				Irrigation production system			
		Date of emergence (No)	Days to 90% heading (No)	Days to maturity (No)	Population density/m ² (No)	Date of emergence (No)	Days to 90% heading (No)	Days to maturity (No)	Population density/m ² (No)
Replication (R)	2	0.62	1.23	35.33	62.77	0.03	1.2	2.8	2080.0
Year (Y)	1	4.80 ^{ns}	504.3 ^{ns}	607.5*	1687.5*	0.01 ^{ns}	2.7 ^{ns}	2.7 ^{ns}	187.5 ^{ns}
Cultivar (C)	19	9.37**	54.57**	22.27*	3767.04**	3.54**	45.6**	46.8**	21321.1**
Y*C	19	0.53 ^{ns}	5.35 ^{ns}	11.92 ^{ns}	11.29 ^{ns}	0.31 ^{ns}	0.3 ^{ns}	0.33 ^{ns}	10.3 ^{ns}
Error	78	1.16	11.71	7.07	249.44	0.66	10.7	11.1	774.9
Grand mean		7.7	61.4	111.65	123.05	6.12	59.3	106.9	237.9
CV (%)		14.01	5.57	2.38	12.84	13.32	5.51	3.11	11.70
DMRT (5%)		2.28	7.24	5.62	33.41	1.73	6.91	7.03	58.88

ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. D.F= Degree of freedom, Y*C = Combined effect of year with cultivar, DMRT (5%) = Duncan's multiple range test at 5 percent, and CV (%) = Percentage of coefficient of variation.

Table 2.4. Phenological responses of durum wheat cultivars under rain-fed and irrigated production systems (data combined over the 2020 and 2021 cropping years).

Cultivars	Rain-fed production system				Irrigation production system			
	Days of emergence	Days to 90% heading	Days to maturity	Population density/m ²	Days of emergence	Days to 90% heading	Days to maturity	Population density/m ²
<i>Alemtena</i>	7 ^{cd}	63 ^{a-c}	113 ^{ab}	135 ^{a-f}	6 ^{a-c}	61.5 ^{a-c}	107.0 ^{a-d}	279.0 ^{ab}
<i>Bakalcha</i>	9.5 ^{ab}	65 ^a	109 ^b	85 ^j	7 ^a	62.5 ^{ab}	102.5 ^d	153.0 ^e
<i>Bullalla</i>	7.5 ^{b-d}	64 ^{ab}	109 ^b	89 ^{ij}	6.5 ^{a-c}	62.0 ^{ab}	102.5 ^d	155.5 ^e
<i>Denbi</i>	7 ^{cd}	60 ^{a-c}	111 ^{ab}	116 ^{d-j}	6.3 ^{a-c}	59.0 ^{a-c}	104.5 ^{b-d}	163.5 ^e
<i>Dire</i>	6.5 ^d	65 ^a	109 ^b	108 ^{e-j}	5.8 ^{a-c}	62.5 ^{ab}	105.0 ^{a-d}	154.0 ^e
<i>Donmateo</i>	6.5 ^d	56 ^c	113 ^{ab}	130 ^{b-g}	5.8 ^{a-c}	55.0 ^c	107.0 ^{a-d}	260.5 ^{a-c}
<i>Ejersa</i>	7 ^{cd}	65 ^a	115 ^a	120 ^{c-i}	5.2 ^{bc}	62.5 ^{ab}	107.0 ^{a-d}	270.0 ^{ab}
<i>Fetan</i>	6.5 ^d	64 ^{ab}	110 ^{ab}	102 ^{f-j}	5 ^c	62.0 ^{ab}	103.5 ^{cd}	169.5 ^e
<i>Gerardo</i>	7 ^{cd}	59 ^{a-c}	113 ^{ab}	98 ^{g-j}	5 ^c	57.0 ^{a-c}	107.0 ^{a-d}	197.0 ^{de}
<i>Hitosa</i>	8.5 ^{a-d}	61 ^{a-c}	110 ^{ab}	144 ^{a-d}	7 ^a	59.0 ^{a-c}	109.0 ^{a-d}	294.5 ^{ab}
<i>Mangudo</i>	9.5 ^{ab}	58 ^{a-c}	114 ^{ab}	150 ^{a-c}	7 ^a	56.0 ^{bc}	111.0 ^{ab}	303.0 ^{ab}
<i>Mokiye</i>	7 ^{cd}	57 ^{bc}	110 ^{ab}	127 ^{b-h}	6 ^{a-c}	56.0 ^{bc}	106.5 ^{a-d}	250.0 ^{b-d}
<i>Obsa</i>	6.5 ^d	64 ^{ab}	113 ^{ab}	96 ^{h-j}	6.1 ^{a-c}	63.0 ^a	106.0 ^{a-d}	193.0 ^{de}
<i>Tate</i>	9.5 ^{ab}	61 ^{a-c}	114 ^{ab}	155 ^{ab}	7 ^a	60.0 ^{a-c}	109.0 ^{a-d}	300.5 ^{ab}
<i>Tesfaye</i>	10 ^a	59 ^{a-c}	113 ^{ab}	159 ^{ab}	7 ^a	57.0 ^{a-c}	112.0 ^a	308.0 ^{ab}
<i>Toltu</i>	7 ^{cd}	65 ^a	111 ^{ab}	93 ^{ij}	5 ^c	61.0 ^{a-c}	104.5 ^{b-d}	208.5 ^{c-e}
<i>Ude</i>	6.5 ^d	61 ^{a-c}	109 ^b	110 ^{e-j}	5 ^c	59.0 ^{a-c}	105.0 ^{a-d}	206.0 ^{c-e}
<i>Utuba</i>	9 ^{a-c}	59 ^{a-c}	113 ^{ab}	168 ^a	6.8 ^{ab}	56.5 ^{a-c}	111.0 ^{ab}	310.0 ^a
<i>Werer</i>	9 ^{a-c}	58 ^{a-c}	112 ^{ab}	140 ^{a-e}	6.8 ^{ab}	55.0 ^c	110.0 ^{a-c}	300.0 ^{ab}
<i>Yerer</i>	7 ^{cd}	64 ^{ab}	112 ^{ab}	136 ^{a-e}	6 ^{a-c}	59.5 ^{a-c}	107.0 ^{a-d}	282.5 ^{ab}
Grand mean	7.7	61.4	111.65	123.05	6.12	59.3	106.9	237.9
DMRT (5%)	2.28	7.23	5.62	33.41	1.73	6.91	7.03	58.88
CV (%)	14.01	5.57	2.38	12.84	13.32	5.51	3.11	11.70
LS	**	**	*	**	*	**	**	**

Mean followed by the same letter are non-significant. DMRT (5%) = Duncan's multiple range test at 5 percent, CV (%) = Percentage of coefficient of variation, and LS=Level of significance.

Table 2.5. The pair-wise T-test analysis of phenological and growth of durum wheat cultivars under rain-fed and irrigated production systems (data combined over the 2020 and 2021 cropping years).

Tested	Irrigation	Rain-fed	Mean difference	Standard deviation	P-value	T _{test}		L.C.I 95%	U. C.I 95%
						T _{cal}	T _{tab}		
DTE	6.12	7.7	-1.58	0.05	0.01	29.1	9.9	97.84	131.9
DTH	59.3	61.4	-2.1	2.06	0.41	1.02	0.29	-10.94	6.744
DTM	106.9	111.7	-4.8	2.46	0.19	1.89	0.8	-15.2	5.94
PDM ²	237.9	123.05	114.85	3.95	0.0012	29.06	9.92	97.84	131.8

DTE= Days to emergence, DTH= Days to heading, DTF= Days to flowering DTM= Days to maturity, PDM²= Population density/m² L.C.I= Low confidential Interval at 95%, U.C.I= Upper confidential Interval at 95%.

Days to physiological maturity

In the rain-fed system, combined data analysis of variance over the two years indicates that both cultivar and year had a significant effect ($p \leq 0.05$) on the physiological maturity of durum wheat. However, the interaction effect of year and cultivar did not significantly affect ($p > 0.05$) the number of days required to reach physiological maturity. Under the irrigated production system, the cultivar showed significant differences in their physiological maturity at $p \leq 0.01$. Conversely, the tested year and the interaction effect of year and cultivar did not affect the maturity of durum wheat at $p > 0.05$ (Table 2.3).

Under the rain-fed production system, the number of days required to reach physiological maturity for the tested cultivars ranged from 109 to 115 days (Table 2.4). The cultivar *Ejersa* matured later, while the cultivars *Bakalcha*, *Bullalla*, *Dire*, and *Ude* matured earlier, with these cultivars being statistically similar to all the tested cultivars except for *Ejersa* (Table 2.4). Under the irrigated production system, the cultivar *Tesfaye* required a longer period to reach physiological maturity, while the cultivars *Bakalcha* and *Bullalla* matured earlier (Table 2.4). The results of the current research indicate that the cultivars influenced the maturity days of wheat even under different growing conditions. The differences in the maturity of durum wheat observed in both the rain-fed and irrigated production systems are clearly associated with the genetics of the cultivars. In this regard, Tanin *et al.* (2022) also reported that wheat cultivars required 90 to 145 number of days to reach physiological maturity.

The pairwise T-test results revealed that the rain-fed production system increased the number of days required to reach physiological maturity of durum wheat by 4.5% compared to the

irrigated system (Table 2.5). The earlier maturity of durum wheat in the irrigated production system, compared to the rain-fed system, is due to soil moisture content and relatively higher temperature it more suitable environmental condition for durum wheat growth and development and finally for higher yield. The application of water in the irrigated system was synchronized with the critical stages of the crop, which may enhance growth and development, thus shortening the maturity period. Additionally, the monthly temperature during the irrigated production was relatively higher which compared to the temperature recorded during the rain-fed experiment it leads to may accelerate the growth stage and result in a reduced maturity duration. In this regard, Mazengo *et al.* (2023) reported that the irrigated production system significantly accelerates the growth and development of wheat by 5 to 10 days compared to the rain-fed production system. Similarly, Iwańska *et al.* (2020) reported that wheat cultivars may require different growing conditions to express their genetic potential.

Population density per meter square

The combined data analysis of variance over the two years indicates that population density per square meter was significantly affected by the main effect of cultivar at $p \leq 0.01$ in both production systems. However, the interaction effect of the factors did not significantly affect this parameter in either production system at $p > 0.05$ (Table 2.3).

In the irrigated production system, the population density of the tested cultivars ranged from 153 to 310 plants per square meter (Table 2.4). The highest population density was observed in the *Utuba* cultivar, while the lowest was recorded for the *Bakelcha* cultivar (Table 2.4). In contrast, in the rain-fed production system, the population densities of the tested cultivars ranged from 85 to 168 plants per square meter. Once again, the highest population density was found in the *Utuba* cultivar, while the smallest was recorded for the *Bakelcha* cultivar at $p \leq 0.05$ (Table 2.4). These research results suggest that the variability in population density among the tested cultivars may be due to genetic differences that respond to the weather conditions of the area under investigation. Numerous studies have also reported that the genetic variability of cultivars affects the total tiller count or population density of wheat (van Frank *et al.*, 2020).

The results of the pairwise T-test analysis indicated that the irrigated production system increased the population density by 93.3% compared to the rain-fed production system (Table

2.5). The variations in population density between the production systems may be attributed to soil moisture stress during the critical period of the crop (Table 1.2). The previous result also indicated that the irrigated system increased the population densities to between 400 and 500 plants of wheat at 1 m² of plot size (Bastos *et al.*, 2020), while under the rain-fed system, the population density ranged from 192 to 271 plants per meter square of land (Akhter *et al.*, 2017).

2.3.2. Responses of Growth and Yield Related Trait of Durum Wheat Cultivars to Irrigated and Rain-fed Production Systems.

2.3.2.1. Growth and yield related parameters

Number of productive tillers per plant

Under the rain-fed production system, the combined analysis of variance over the two years showed that the year, cultivar, and their interactions significantly influenced the number of productive tillers per plant at $p \leq 0.01$. In the irrigated production system, only the cultivar had a significant effect ($p \leq 0.01$) on the number of productive tillers per plant (Table 2.6).

In the rain-fed production system, the cultivar *Utuba* recorded the highest number of productive tillers per plant, which was statistically similar to the number produced by the cultivar *Tesfaye*. In contrast, the cultivars *Bakalcha*, *Bullalla*, and *Toltu* recorded the lowest number of productive tillers per plant (Table 2.7). Similarly, the cultivar *Utuba* also recorded the highest number of productive tillers per plant in the irrigated production system, which was statistically similar to the numbers produced by the *Mangudo* and *Tesfaye* cultivars. The number of productive tillers is one of the most important parameters influencing the number of heads and spikes, and thus the grain yield of a given wheat cultivar (Wang *et al.*, 2016). The variations in tillering capacity among the cultivars observed in both the rain-fed and irrigated production systems are clearly related to the genetics of the cultivars. In this regard, research findings from various scholars have reported that wheat cultivars differ in their tillering capacities based on their genetic makeup, which is consistent with the findings of the present study (Liu *et al.*, 2020; Shang *et al.*, 2021).

The pairwise T-test analysis showed that the irrigated production system increased the number of productive tillers of durum wheat cultivars compared to the rain-fed production system. Regardless of the cultivars, the irrigated production system increased the number of productive tillers per plant by 83.7% compared to the rain-fed production system (Table 2.8).

The increase in the number of productive tillers per plant in the irrigated production system is likely related to environmental suitability, where water application was aligned with the critical growth stages of the plants. The prevailing high temperatures and the absence of diseases and insect pests may also contribute to the enhanced growth and development of plants, including the number of productive tillers per plant, in the irrigated production system. Previous research has indicated an increase in effective tillers of wheat cultivars due to higher temperatures (Tilley *et al.*, 2019; Chavan *et al.*, 2022).

Plant height

The results of the combined data analysis over the two years indicated that the cultivar ($p \leq 0.01$) significantly affected the plant height of durum wheat, while their interaction did not influence this parameter in the rain-fed production system. In the irrigated system, the cultivar influenced plant height ($p \leq 0.05$), whereas the cropping year and its interaction with the cultivar did not significantly affect the plant height of durum wheat ($p > 0.05$) (Table 2.6).

The the two years' interaction result indicated that the tallest plant height was recorded for the *Gerardo* cultivar, while the *Bakalcha* cultivar exhibited the shortest plant height in both rain-fed and irrigated production systems (Table 2.7). The variations in plant height among durum wheat cultivars observed in both rain-fed and irrigated production systems could be attributed to genetic differences. These findings are consistent with those of Gao *et al.* (2020), who reported considerable variations in the plant heights of different wheat cultivars. According to the report by Góral *et al.* (2019), the plant height of wheat is significantly influenced by the genetic variability of the cultivars.

The pairwise t-test analysis revealed that the irrigated production system increased plant height by 9.2% compared to the same cultivars tested under the rain-fed production system (Table 2.8). The increased plant height of durum wheat in the irrigated production system, compared to that in the rain-fed system, could be attributed to the balanced water supply tailored to the growth stages of the plants, as well as the higher temperatures that prevailed during the irrigated production system compared to the rain-fed production system. The findings of this study are supported by scholars who have indicated that the amount of soil moisture and the genetic variations of cultivars affect the plant height of wheat (Branković *et al.*, 2015).

Table 2.6. Mean square values for grain yield and yield related traits of durum wheat cultivars under rain-fed and irrigated production systems (data combined over the 2020 and 2021 cropping years).

Source of variation	D.F	Rain-fed production system					Irrigation production system				
		Effective tiller/Plant (No)	Plant height (cm)	Spike length (cm)	Spikelet/ Spike (No)	Kernel/ Spike (No)	Effective tiller/Plant (No)	Plant height (cm)	Spike length (cm)	Spikelet/ Spike (No)	Kernel/ Spike (No)
Replication (R)	2	0.02	38.03	0.53	0.18	25.5	0.13	17.3	0.9	2.78	23.12
Year (Y)	1	33.0**	456.3*	0.06 ^{ns}	4.80 ^{ns}	2284*	1.023 ^{ns}	63.1 ^{ns}	0.43 ^{ns}	10.80 ^{ns}	37.9 ^{ns}
Cultivar (C)	19	13.2**	332.8**	8.88**	35.9**	345.6**	22.6*	210.4*	20.6**	50.6*	353**
Y*C	19	0.75**	4.09 ^{ns}	0.03 ^{ns}	1.17 ^{ns}	47.33*	0.09 ^{ns}	1.5 ^{ns}	0.03 ^{ns}	2.27 ^{ns}	2.12 ^{ns}
Error	78	0.11	80.87	0.55	3.02	14.56	0.36	48.2	0.8	5.13	32.25
Grand mean		2.58	84.95	5.56	13.20	31.70	4.74	92.8	8.1	17.8	54.76
CV (%)		12.79	10.59	13.35	13.17	12.04	12.71	7.48	11.06	12.73	10.37
DMRT (5%)		0.69	19.02	1.57	3.68	8.07	1.27	14.68	1.89	4.79	12.01

ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. D.F= Degree of freedom, Y*C = Combined effect of year with cultivar, CV (%) = Percentage of coefficient of variation, DMRT (5%) = Duncan's multiple range test at 5 percent.

Table 2.7. Growth and yield related responses of durum wheat cultivars under the rain-fed and irrigated production systems (data combined over the 2020 and 2021 cropping years).

Cultivars	Rain-fed production system					Irrigation production system				
	Effective tiller/plant (No)	Plant height (cm)	Spike length (cm)	Spikelet/Spike (No)	Kernel/spike(No)	Effective tiller/plant(No)	Plant height (cm)	Spike length (cm)	Spikelet/Spike(No)	Kernel/Spike(No)
<i>Alemtena</i>	2.8 ^f	87 ^{a-e}	5.5 ^{cd}	13.5 ^{b-f}	31.5 ^{b-d}	5.0 ^{de}	93.0 ^{a-d}	8.0 ^{c-e}	18.5 ^{b-e}	56.0 ^{b-g}
<i>Bakalcha</i>	1 ⁱ	70 ^e	4.5 ^d	12.0 ^{d-f}	17.5 ^g	3.0 ^f	81.0 ^d	5.5 ^g	16.0 ^{de}	46.5 ^g
<i>Bullalla</i>	1 ⁱ	71.5 ^{de}	4.5 ^d	12.0 ^{d-f}	18.5 ^{fg}	3.0 ^f	82.0 ^{cd}	6.5 ^{e-g}	16.5 ^{de}	47.0 ^g
<i>Denbi</i>	1.5 ^{hi}	85 ^{a-e}	4.5 ^d	10.0 ^f	28.5 ^{de}	3.0 ^f	90.5 ^{a-d}	6.4 ^{e-g}	14.5 ^e	49.0 ^{fg}
<i>Dire</i>	1.5 ^{hi}	80 ^{a-e}	5.1 ^d	13.5 ^{b-f}	24 ^{d-g}	2.8 ^f	89.5 ^{b-d}	7.4 ^{e-g}	17.5 ^{c-e}	50.5 ^{e-g}
<i>Donmateo</i>	2.5 ^{fg}	90 ^{a-d}	5.5 ^{cd}	12.0 ^{d-f}	38.2 ^{ab}	4.7 ^{de}	96.0 ^{a-c}	7.9 ^{de}	16.0 ^{de}	55.0 ^{c-g}
<i>Ejersa</i>	2 ^{gh}	87.5 ^{a-e}	4.8 ^d	13.0 ^{c-f}	37 ^{a-c}	5.0 ^{de}	93.5 ^{a-d}	7.5 ^{ef}	18.0 ^{c-e}	54.0 ^{c-g}
<i>Fetan</i>	1.3 ⁱ	72 ^{c-e}	4.8 ^d	10.0 ^f	21.5 ^{e-g}	3.0 ^f	86.5 ^{b-d}	7.0 ^{e-g}	14.5 ^e	46.0 ^g
<i>Gerardo</i>	1.3 ⁱ	98 ^a	9.9 ^a	13.0 ^{c-f}	36.7 ^{a-c}	3.3 ^f	105.0 ^a	12.4 ^a	17.5 ^{c-e}	48.3 ^{fg}
<i>Hitosa</i>	4 ^{c-e}	90 ^{a-d}	5.9 ^{cd}	16.0 ^{a-c}	39 ^{ab}	6.0 ^{cd}	97.5 ^{ab}	9.5 ^{b-d}	20.0 ^{b-d}	68.0 ^{ab}
<i>Mangudo</i>	4.3 ^{cd}	89 ^{a-e}	7.5 ^b	18.0 ^a	40 ^a	7.7 ^{ab}	95.0 ^{a-d}	10.4 ^b	25.0 ^a	70.0 ^a
<i>Mokiye</i>	2.5 ^{fg}	85.5 ^{a-e}	4.6 ^d	11.0 ^{ef}	31.5 ^{b-d}	4.0 ^{ef}	92.0 ^{a-d}	6.9 ^{e-g}	16.0 ^{de}	52.5 ^{d-g}
<i>Obsa</i>	1.3 ⁱ	85.2 ^{a-e}	4.9 ^d	11.0 ^{ef}	25.8 ^{d-f}	3.0 ^f	91.5 ^{a-d}	7.0 ^{e-g}	16.0 ^{de}	48.0 ^{fg}
<i>Tate</i>	4.5 ^{bc}	92 ^{ab}	6.7 ^{bc}	15.5 ^{a-d}	39 ^{ab}	6.7 ^{bc}	99.5 ^{ab}	10.0 ^b	21.5 ^{a-c}	66.0 ^{a-c}
<i>Tesfaye</i>	5 ^{ab}	90.5 ^{a-d}	7.5 ^b	17.0 ^{ab}	39.5 ^{ab}	7.9 ^{ab}	98.0 ^{ab}	10.2 ^b	23.0 ^{ab}	63.0 ^{a-d}
<i>Toltu</i>	1 ⁱ	78 ^{b-e}	4.4 ^d	10.5 ^{ef}	23.5 ^{d-g}	3.0 ^f	87.0 ^{b-d}	6.0 ^{fg}	15.0 ^e	48.0 ^{fg}
<i>Ude</i>	1.5 ^{hi}	80.4 ^{a-e}	4.4 ^d	10.5 ^{ef}	29.5 ^{c-e}	3.0 ^f	90.0 ^{b-d}	6.0 ^{fg}	14.5 ^e	48.5 ^{fg}
<i>Utuba</i>	5.5 ^a	91 ^{a-c}	5.9 ^{cd}	16.0 ^{a-c}	38.5 ^{ab}	8.8 ^a	99.5 ^{ab}	9.9 ^{bc}	20.0 ^{b-d}	58.0 ^{a-g}
<i>Werer</i>	3.8 ^{de}	89 ^{a-e}	5.7 ^{cd}	15.5 ^{a-d}	37.6 ^{ab}	6.0 ^{cd}	95.5 ^{a-d}	9.4 ^{b-d}	19.0 ^{b-e}	59.5 ^{a-f}
<i>Yerer</i>	3.5 ^e	87.4 ^{a-e}	5.4 ^{cd}	14.0 ^{b-e}	36.8 ^{a-c}	5.8 ^{cd}	93.0 ^{a-d}	7.4 ^{ef}	17.0 ^{c-e}	61.5 ^{a-e}
Grand mean	2.58	84.95	5.56	13.20	31.70	4.74	92.8	8.1	17.8	54.76
DMRT (5%)	0.69	19.02	1.57	3.68	8.07	1.27	14.68	1.89	4.79	12.01
CV (%)	12.79	10.59	13.35	13.17	12.04	12.71	7.48	11.06	12.73	10.37
MSE±	0.11	80.87	0.55	3.02	14.56	0.36	48.2	0.8	5.13	32.25
LS	**	**	**	**	**	*	*	**	*	**

Mean followed by the same letters are non-significant. DMRT (5%) = Duncan's multiple range test at 5 percent, CV (%) = Percentage of coefficient of variation, and LS=Level of significance.

Table 2.8. The pair-wise T-test analysis of yield related in durum wheat cultivars under the rain-fed and irrigated production systems (data combined over the 2020 and 2021 cropping years).

Param.	Irrigation	Rain-fed	MD	SD	P Value	T _{test}		L.C.I 95%	U. C.I 95%
						T _{cal}	T _{tab}		
<i>PTP⁻¹(No)</i>	4.74	2.58	2.16	0.19	0.05	30	3.8	5.45	6.27
<i>PTH(cm)</i>	92.8	84.95	7.85	2.08	0.06	3.8	1.9	-1.12	16.78
<i>SL(cm)</i>	8.1	5.56	2.54	0.06	0.006	40	32	2.24	2.78
<i>NSLS⁻¹(No)</i>	17.8	13.2	4.6	0.21	0.005	22	3.8	4.13	5.02
<i>NKS⁻¹(No)</i>	54.7	31.7	23.1	4.40	0.035	5.2	4.3	4.12	41.99

PTP⁻¹ = Productive tillers per plant, *PTH* = Plant height *SL* = Spike length, *NSLS⁻¹* = Number of spikelet per spike, *NKS⁻¹* = Number of spikelet per spike, *MD* = Mean difference, *SD* = Standard deviation, *L.C.I* = Low confidential Interval at 95%, *U.C.I* = Upper confidential Interval at 95%.

Spike length

The results of the combined data analysis of variance over the two years revealed that the main effect of cultivar significantly affected the spike length of durum wheat at $p \leq 0.01$, both under irrigated and rain-fed production systems. In contrast, the main effect of the year and the interaction effect of year and cultivar had no significant impact on the spike length of durum wheat in either the rain-fed or irrigated production systems at $p > 0.05$ (Table 2.6).

The combined data result in the irrigated production system, the spike lengths among the tested cultivars ranged from 5.5 to 12.4 cm. The highest spike length was recorded for the cultivar *Gerardo*, followed by the cultivars *Mangudo*, *Tesfaye*, *Tate*, and *Utuba*. In contrast, the smallest spike length was registered for the *Bakalcha* cultivar at $p < 0.01$ (Table 2.8). In the rain-fed production system, the spike lengths of the tested cultivars ranged from 4.5 to 9.9 cm (Table 2.8). Again, the highest spike length was recorded for the *Gerardo* cultivar, while the smallest was registered for the *Bakalcha* cultivar at $p < 0.01$. These results indicate that, among the twenty tested cultivars, the *Gerardo* cultivar exhibits an exceptionally large spike length in both irrigated and rain-fed production systems, which may be attributed to genetic differences in spike length formation.

The effect of production systems on the spike length of durum wheat cultivars was evaluated through pairwise T-test analysis. The results from the T-test indicated that spike length in the irrigated production system increased by 45.7% compared to the cultivars tested under the rain-fed production system (Table 2.8). These findings regarding spike length are consistent with those reported by Knezevic *et al.* (2019), who noted that variability in spike length and

the number of spikelets per spike contributes to grain yield formation in wheat. The differences in spike length and the number of spikelets per spike among the 20 genetically diverse wheat cultivars grown in different seasons underscore this relationship. Thus, spike length influences the number of grains per spike and ultimately affects the total grain yield of the crops.

Number of spikelet per spike

The combined data analysis of variance over the two years demonstrated that the cultivar significantly affected the number of spikelets per spike of durum wheat in both rain-fed ($P \leq 0.01$) and irrigated ($P \leq 0.05$) production systems. However, the main effect of the year and the interaction effect between the year and the cultivars did not significantly influence the number of spikelets per spike of durum wheat under either rain-fed or irrigated production systems at $P > 0.05$ (Table 2.6).

In both rain-fed and irrigated production systems, the *Mangudo* cultivar recorded the highest number of spikelets per spike, while the *Denbi* and *Fetan* cultivars exhibited the lowest (Table 2.7). The variation in spikelet production per spike among the cultivars in both production systems is likely related to the genetic variability of the tested cultivars. Consistent with the results of the present study, Qiao *et al.* (2022) also reported that the genetic factors of the cultivars influenced spikelet production per spike of wheat.

The pairwise t-test analysis indicated that the irrigated production system increased the number of spikelets per spike of durum wheat cultivars by 34.8% compared to the rain-fed production system (Table 2.8). The increase in spikelets per spike of durum wheat in the irrigated production system may be attributed to suitable soil moisture content during the critical growth period of the crop, as well as higher temperatures compared to the rain-fed production system. Previous research has also indicated that both the genetic variation among the cultivars and environmental factors, such as soil water content and temperature, significantly affect the architecture, arrangement, and number of spikelets per spike of wheat (Dixon *et al.*, 2018; Beral *et al.*, 2022).

Number of kernel per spike

The results of the combined data analysis of variance over the years revealed that the main effect of cultivar significantly affected the number of kernels per spike at $p \leq 0.01$ under both

irrigated and rain-fed production systems. Conversely, both the main effect of the tested year and the interaction between year and cultivars significantly affected the number of kernels per spike at $p \leq 0.05$ under the rain-fed production system. However, the main effect of year and the interaction between year and the tested cultivars did not significantly affect the number of kernels per spike under the irrigated production system ($p > 0.05$) (Table 2.6).

Under both rain-fed and irrigated production systems, the number of kernels per spike for the tested cultivars ranged from 18 to 40 and from 46 to 70, respectively. In the rain-fed production system, the highest and lowest numbers of kernels per spike were recorded for the *Mangudo* and *Bakalcha* cultivars, respectively. In the irrigated system, the highest number of kernels per spike was observed in the *Mangudo* cultivar, while the lowest was recorded for the *Fetan* cultivar (Table 2.7). The differences in the number of kernels per spike may be attributed to the genetic variability among the tested cultivars in both production systems. Genetic variation in wheat cultivars impacts the production of kernels per spike (Kuzay *et al.*, 2019), which aligns with the findings of the present study.

The pairwise t-test analysis indicated that the number of kernels per spike in the irrigated production system increased by 72.6% compared to the rain-fed production system (Table 2.8). This increase can be attributed to the fact that the irrigated production system provides adequate soil moisture content and temperature during the critical growth stages of the crop, in contrast to the rain-fed production system. Research results also indicate that, under optimal environmental conditions including adequate water availability during the critical period of the crop increased the number of kernels per spike in wheat by a range of 36% to 56% (Mirbahar *et al.*, 2009; Kuzay *et al.*, 2022).

2.3.3. Responses of Grain and Biomass Yield of Durum Wheat Cultivars to Irrigated and Rain-fed Systems.

2.3.3.1. Yield parameters

Grain yield

In the rain-fed production system, the combined analysis of variance over the years revealed that the effects of cultivar ($p \leq 0.01$) and cropping years ($p \leq 0.05$) significantly influenced the grain yield of durum wheat; however, their combined effect did not significantly affect this parameter ($p > 0.05$). Under the irrigated production system, the effect of cultivar

significantly affected ($p \leq 0.05$) the grain yield, while the cropping year and its interaction with cultivar did not have a significant effect ($p > 0.05$) on this parameter (Table 2.9).

The grain yields of the tested cultivars under the rain-fed and irrigated production systems ranged from 667.5 kg ha⁻¹ to 4925 kg ha⁻¹ and from 4101.7 kg ha⁻¹ to 6225 kg ha⁻¹, respectively. In the rain-fed production system, the highest grain yield per hectare was recorded by the *Mangudo*, *Tesfaye*, *Utuba*, *Hitosa*, and *Tate* cultivars, which were statistically similar to each other; conversely, the lowest grain yield was recorded for the *Bakalcha*, *Bullalla*, and *Fetan* cultivars. In the irrigated production system, the *Tesfaye*, *Mangudo*, and *Utuba* cultivars achieved the highest grain yields, while the *Bakalcha* and *Bullalla* cultivars recorded the lowest grain yields (Table 2.10).

The variation in grain yield among the durum wheat cultivars in both production systems may be attributed to the genetic variability of the tested cultivars. In line with the results of the present study, earlier research findings also indicated that the yield of wheat is influenced by the genetic characteristics of the cultivars (Karaman, 2019; Gerard *et al.*, 2020; Boussakouran *et al.*, 2021).

The result of the pair-wise T-test analysis indicated that, irrespective of the cultivars, the irrigated system increased the grain yield of durum wheat by 69.1% compared to the rain-fed production system. This variation in grain yield is likely associated with environmental differences between the two production systems. Plants grown under the irrigated production system received irrigation water based on their critical growth stages (Table 2.11), and the temperature under irrigation conditions was relatively higher, which enhanced plant growth and development, leading to increased grain yield compared to the rain-fed conditions, where rainfall was higher and temperature was relatively lower. Lack of biotic stress under irrigated production system could also contribute to the increased grain yield of durum wheat as compared to rain-fed system. The results of the present study are supported by previous research findings, which showed that the grain yield of winter wheat in the irrigation production system increased by 40% compared to the rain-fed production system (Hordofa *et al.*, 2022). Similarly, other scholars have observed increased wheat grain yield in the irrigation production system compared to the rain-fed production system (Xie *et al.*, 2017; Kuzay *et al.*, 2022).

Biomass yield

The results of the combined data analysis of variance over the two years indicated that cultivar significantly influenced the biomass yield of durum wheat under both rain-fed ($p \leq 0.01$) and irrigated ($p \leq 0.05$) production systems. However, the cropping year and its interaction with cultivars did not significantly affect ($p > 0.05$) the biomass yield of durum wheat in either production system (Table 2.9).

In the rain-fed production system, the cultivars *Mangudo*, *Tesfaye*, *Utuba*, and *Tate* recorded the highest biomass yield per hectare, while in the irrigated production system, the cultivars *Tate*, *Utuba*, *Hitosa*, *Mangudo*, and *Tesfaye* achieved the highest yields. Conversely, the *Bakalcha* and *Bullalla* cultivars produced the lowest biomass yield in both production systems (Table 2.10). The variation in biomass yield among the durum wheat cultivars observed in the present study may be attributed to the genetic variability among the tested cultivars. Such variability in biomass yield production has also been reported by Qin *et al.* (2019) and Maeoka *et al.* (2020).

The pair-wise T-test analysis of the combined data over the years indicated that the irrigated production system increased the biomass yield of durum wheat cultivars by 56.3% compared to the rain-fed production system, demonstrating the environmental suitability of the irrigated system (Table 2.11). Plants grown under the irrigated production system received irrigation water based on their critical growth stages, and the temperature under irrigation conditions was relatively higher, which enhances the growth and development of the plants. This in turn led to increased biomass yield compared to the rain-fed conditions, where rainfall was higher and temperatures were relatively lower. Furthermore, Lack of biotic stress under irrigated production system could also contribute to the increased biomass yield of durum wheat as compared to rain-fed system. The results of the present study are consistent with the findings of Wang *et al.* (2019), who reported an increase in biomass yield in the irrigated system compared to the rain-fed wheat production system.

Table 2.9. Mean square values for yield of durum wheat cultivars under rain-fed and irrigated production systems (data combined over the 2020 and 2021 cropping years)

Source of variation	D.F	Rain-fed production system				Irrigation production system			
		Grain yield (kg ha ⁻¹)	Biomass yield (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)	Harvest index (%)	Grain yield (kg ha ⁻¹)	Biomass yield (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)	Harvest index (%)
Replication(R)	2	474142	859750	33005	33.06	4333	2395750	16500	37.5
Year (S)	1	866490*	27000.0 ^{ns}	13457.8 ^{ns}	1278.9*	25960 ^{ns}	2207378 ^{ns}	5004 ^{ns}	41.1 ^{ns}
Cultivar (C)	19	1118000**	5617000**	1734000**	8.15 ^{ns}	3049121*	6483766*	182000**	83.2**
Y*C	19	28598.7 ^{ns}	20000.1 ^{ns}	28325 ^{ns}	98.65**	8063 ^{ns}	1291165 ^{ns}	2000 ^{ns}	5.4 ^{ns}
Error	78	145022	993596	25000	26.08	431000	2226177	35900	22.1
Grand mean		2901.0	6758.1	3857.1	42.53	4904.7	10562.0	5657	46.5
CV (%)		13.13	14.75	12.87	12.01	13.39	14.13	10.59	10.12
DMRT (5%)		805.47	2108.3	1050.1	16.8	1388.6	3155.8	1260.0	9.95

*ns, *and ***, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. D.F= Degree of freedom, Y*C = Combined effect of year with cultivar, CV (%) = Percentage of coefficient of variation, DMRT (5%) = Duncan's multiple range test at 5 percent.

Table 2.20. Grain yield and yield related responses of durum wheat cultivars under the rain-fed and irrigated production systems (data combined over the 2020 and 2021 cropping years)

Cultivars	Rain-fed production system				Irrigation production system			
	Grain yield (kg ha ⁻¹)	Biomass yield (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)	Harvest index (%)	Grain yield (kg ha ⁻¹)	Biomass yield (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)	Harvest index (%)
<i>Alemtena</i>	3040.9 ^{de}	7206 ^{d-f}	4165.1 ^{de}	42.3	4585.0 ^{c-e}	11785 ^a	7200 ^a	38.9 ^c
<i>Bakalcha</i>	667.5 ^j	1608 ^k	940.5 ^j	41.5	4101.7 ^e	8628 ^b	4526.3 ^d	47.5 ^{a-c}
<i>Bullalla</i>	805.0 ^{ij}	1931 ^{jk}	1126 ^{ij}	41.7	4300.0 ^{de}	9216 ^{ab}	4916 ^{cd}	46.7 ^{bc}
<i>Denbi</i>	2175.0 ^{f-h}	5166 ^{f-i}	2991 ^{f-h}	42.1	4450.0 ^{de}	10001 ^{ab}	5551 ^{b-d}	44.5 ^{bc}
<i>Dire</i>	1637.5 ^{gh}	3871 ^{h-j}	2234 ^h	42.3	4525.0 ^{de}	9681 ^{ab}	5156 ^{b-d}	46.7 ^{bc}
<i>Donmateo</i>	4055.0 ^{bc}	9497 ^{a-c}	5442 ^{a-d}	42.7	4700.0 ^{b-e}	10489 ^{ab}	5789 ^{b-d}	45.3 ^{bc}
<i>Ejersa</i>	3459.1 ^{cd}	8120 ^{c-e}	4660.9 ^{cd}	42.6	4602.5 ^{c-e}	10294 ^{ab}	5691.5 ^{b-d}	44.7 ^{bc}
<i>Fetan</i>	1375.0 ^{h-j}	3526 ^{i-k}	2151 ^{hi}	39.9	4400.0 ^{de}	9884 ^{ab}	5484 ^{b-d}	44.5 ^{bc}
<i>Gerardo</i>	2625.0 ^{ef}	6191 ^{e-g}	3566 ^{ef}	42.4	4425.0 ^{de}	9943 ^{ab}	5518 ^{b-d}	44.5 ^{bc}
<i>Hitosa</i>	4350.0 ^{ab}	9932 ^{a-c}	5582 ^{a-c}	43.8	5645.0 ^{a-d}	11716 ^{ab}	6071 ^{a-c}	48.2 ^{a-c}
<i>Mangudo</i>	4925.0 ^a	11205 ^a	6280 ^a	43.9	6200.0 ^a	11689 ^{ab}	5489 ^{b-d}	53.0 ^{ab}
<i>Mokiye</i>	2442.0 ^{e-g}	5759 ^{f-h}	3317 ^{fg}	42.4	4540.0 ^{de}	10180 ^{ab}	5640 ^{b-d}	44.6 ^{bc}
<i>Obsa</i>	1785.0 ^{gh}	4220 ^{g-i}	2435 ^{gh}	42.3	4405.0 ^{de}	9835 ^{ab}	5430 ^{b-d}	44.8 ^{bc}
<i>Tate</i>	4419.1 ^{ab}	10067 ^{a-c}	5647.9 ^{a-c}	43.9	5940.0 ^{a-c}	12322 ^a	6382 ^{ab}	48.0 ^{a-c}
<i>Tesfaye</i>	4625.0 ^{ab}	10464 ^a	5839 ^a	44.2	6225.0 ^a	11680 ^{ab}	5455 ^{b-d}	56.7 ^a
<i>Toltu</i>	1490.0 ^{hi}	3548 ^{i-k}	2058 ^{hi}	41.9	4325.0 ^{de}	9739 ^{ab}	5414 ^{b-d}	44.4 ^{bc}
<i>Ude</i>	2097.5 ^{f-h}	4982 ^{g-i}	2884.5 ^{f-h}	42.1	4445.0 ^{de}	9989 ^{ab}	5544 ^{b-d}	44.5 ^{bc}
<i>Utuba</i>	4560.0 ^{ab}	10364 ^{ab}	5804 ^{ab}	43.9	6025.0 ^{ab}	11852 ^a	5827 ^{bc}	50.8 ^{ab}
<i>Werer</i>	3975.0 ^{bc}	9244 ^{a-d}	5269 ^{a-d}	43.0	5480.0 ^{a-e}	11644 ^{ab}	6164 ^{a-c}	47.1 ^{a-c}
<i>Yerer</i>	3510.9 ^{cd}	8261 ^{b-e}	4750.1 ^{b-d}	42.5	4775.0 ^{b-e}	10663 ^{ab}	5888 ^{bc}	44.8 ^{bc}
Grand mean	2901.0	6758.1	3857.1	42.9	4904.7	10562.0	5657.3	46.4
DMRT (5%)	805.47	2108.3	1.05	10.8	1388.6	3155.8	1260.1	9.95
CV (%)	13.13	14.75	12.87	12.01	13.39	14.13	10.59	10.12
MSE±	145022	993596	25000	26.08	431000	2226177	35900	22.1
LS	**	**	**	ns	*	*	**	**

Mean followed by the same letters are non-significant. DMRT (5%) = Duncan's multiple range test at 5 percent, CV (%) = Percentage of coefficient of variation, and LS=Level of significance.

Table 2.31. The pair-wise T-test analysis of grain yield of durum wheat cultivars under the rain-fed and irrigated production systems (data combined over the 2020 and 2021 cropping years)

parameter	Irrigation	Rain-fed	MD	SD	P _{value}	T _{test}		L.C.I 95%	U. C.I 95%
						T _{cal}	T _{tab}		
GY (kg ha ⁻¹)	4904.7	2901	2004	0.11	0.003	17.6	4.3	1.51	2.49
BY (kg ha ⁻¹)	10562	6758	3804	0.16	0.005	8.2	3.8	1.40	2.49
SY (kg ha ⁻¹)	5657.3	3857.1	1800	0.09	0.002	20.4	9.92	1.40	2.16
HI (%)	46.4	42.9	3.5	3.31	0.35	1.20	0.29	-10.27	18.23

GY (kg ha⁻¹) = Grain yield kilogram per hectare, BY (kg ha⁻¹) = Biomass yield kilogram per hectare, SY (kg ha⁻¹) = Straw yield kilogram per hectare, HI (%) = Harvest index in percentage, MD= Mean difference, SD= Standard deviation L.C.I= Low confidential Interval at 95%, U.C.I= Upper confidential Interval at 95%.

Straw yield

The results of the combined data analysis of variance over the two years indicated that the straw yield was significantly affected by the main effect of the cultivar at $p \leq 0.01$ under both irrigated and rain-fed production systems. In contrast, the main effect of the year and the interaction effect of the year with the cultivar had no significant impact on the straw yield of durum wheat under either production system at $p > 0.05$ (Table 2.9).

Under the irrigated production system, the combined analysis over the years indicated that the straw yield ranged from 4,526 to 7,200 kg ha⁻¹. The *Alemtena* cultivar produced the highest straw yield per hectare, showing no statistically significant difference compared to the *Hitosa*, *Tate*, and *Werer* cultivars at $p \leq 0.01$. Conversely, the *Bakalcha* cultivar recorded the lowest straw yield per hectare (Table 2.10).

In the rain-fed production system, the tested cultivars produced straw yields per hectare ranging from 940 to 6,280 kg ha⁻¹. The highest straw yield per hectare was recorded for the *Mangudo* cultivar, which was statistically non-significant compared to the *Donmateo*, *Hitosa*, *Tesfaye*, *Tate*, *Utuba*, and *Werer* cultivars at $p > 0.05$. Meanwhile, the *Bakalcha* cultivar again had the lowest straw yield (Table 2.11). These results indicate that the *Alemtena* and *Mangudo* cultivars had higher straw yield production under irrigated and rain-fed systems, respectively, while the *Bakalcha* cultivar had the lowest straw yield per hectare in cropping systems. Therefore, the current research suggests that higher straw yield production is influenced by the cultivars, likely due to the genetic factor variability among them regarding straw yield production. Previous research has also shown that straw yield and harvest index significantly differ between and among wheat classes (Dai *et al.*, 2016).

The difference in straw yield per hectare under irrigated and rain-fed production systems was analyzed using a pairwise T-test, which indicated that straw yield under the irrigated production system increased by 46.7% compared to the rain-fed production system (Table 2.11). In Ethiopia, mixed agriculture comprising both crop and livestock farming is predominant among farmers living in the highland areas of the country, and straw production for livestock feed is a major concern. Consequently, the use of the *Alemtena* cultivar for straw production in irrigated systems and the *Mangudo* cultivar for rain-fed systems is preferable.

Harvest index

Under the irrigated production system, the combined data analysis of variance over the two years revealed that the main effect of the cultivar significantly affects the harvest index of durum wheat at $p \leq 0.05$, while year and its interaction with cultivars had no effect on the harvest index of durum wheat. In contrast, under the rain-fed production system, the main effect of the year and the interaction effect of the tested year and cultivar significantly affected the harvest index of durum wheat at $p \leq 0.05$ and $p < 0.01$, respectively, whereas the main effect of cultivars did not significantly affect the harvest index at $p > 0.05$ (Table 2.9).

Under the irrigated production system, the harvest index among the tested cultivars ranged from 38.9% to 56.7%. The *Tesfaye* cultivar provided the highest harvest index, while the lowest was recorded by the *Alemtena* cultivar (Table 2.10). The variations in the harvest index among the cultivars under the irrigated production system may be attributed to differences in grain and straw yields. Thus, not only *Tesfaye* but also *Mangudo*, *Tate*, and *Utuba* cultivars produced large harvest index percentages with differences compared to *Tesfaye* (Table 2.10). As a result, *Tesfaye*, *Mangudo*, *Tate*, and *Utuba* cultivars exhibit the capacity to produce a grain yield greater than the straw yield compared to the other tested cultivars under the irrigated production system. The present research findings align with previous studies, indicating that the harvest index of wheat varies among cultivars under an irrigated production system (Kobata *et al.*, 2018).

However, in the rain-fed production system, the main effect of the cultivar did not affect the harvest index of durum wheat; this may be due to the lack of variability between the grain and straw yields in this system (Table 2.11). In this regard, previous research has similarly

reported that the harvest index was not affected by cultivar or N-fertilization in the rain-fed production system (Wang *et al.*, 2020).

The T-test results indicated that the harvest index recorded under the irrigated production system increased by 8.2% compared to the rain-fed system (Table 2.11). Therefore, the tested cultivars demonstrate a higher harvest index under the irrigated production system compared to those tested under the rain-fed production system. For this reason, the irrigated production system is more suitable for grain yield production than the rain-fed season, leading to a higher harvest index value, likely due to soil moisture variability between the production systems at critical stages of crop growth. In this context, the current study supports earlier research, which found that the irrigated growing season increased wheat production by 22% compared to the rain-fed growing season (Liu *et al.*, 2022).

2.3.4. Grain Quality Response of Durum Wheat Cultivars to Irrigated and Rain-fed Production Systems.

2.3.4.1. Grain quality parameters

Thousand kernel weight

The analysis of variance conducted over the two years indicates that both cultivar and cropping year significantly influenced the thousand kernel weight of durum wheat under a rain-fed system ($p \leq 0.01$). In contrast, under irrigated conditions, the cultivar significantly impacted thousand kernel weight ($p \leq 0.05$), while the cropping year did not present a significant effect ($p > 0.05$) (Table 2.12).

In the rain-fed production system, the thousand kernel weight ranged from 24 g to 48.3 g, whereas in the irrigated system, it varied from 38.5 g to 51.8 g. Notably, the cultivars *Tate*, *Mangudo*, and *Tesfaye* exhibited the highest thousand kernel weights in both production systems, as well as *Hitosa* under irrigated system and these weights were statistically comparable among them (Table 2.13). Conversely, the cultivars *Denbi*, *Fetan*, and *Obsa* demonstrated the lowest thousand kernel weights in the rain-fed system, while *Bakalcha* and *Bullalla* had the lowest in the irrigated system; these were statistically similar to one another within each respective system.

The differences in thousand kernel weight among cultivars in both production systems may be attributed to genetic factor of the tested cultivars and the climatic requirement of the cultivars to their growing conditions. This finding aligns with that of Aktas (2020) and Farkas *et al.* (2020), who noted that thousand kernel weights are primarily influenced by cultivars' responses to their specific environments.

Moreover, the pairwise T-test analysis of the combined data showed that irrigated production systems resulted in a significant 33.4% increase in thousand kernel weight compared to rain-fed systems (Table 2.14). This improvement is likely linked to more favorable conditions, such as adequate soil moisture, higher relative atmospheric temperatures, and a reduced incidence of diseases and pests in irrigated systems. These factors contribute to better vegetative growth and grain filling, leading to higher thousand kernel weights. In line with this, Jabbour *et al.* (2023) emphasized that inadequate water supply during the grain-filling period negatively affects thousand kernel weight and ultimately reduces wheat yield.

Hectoliter weight

The results of the combined analysis of variance over the two years revealed that the cultivar influenced the hectoliter weight of durum wheat in both rain-fed ($p \leq 0.01$) and irrigated ($p \leq 0.05$) production systems. The cropping year and its interaction with the cultivar in rain-fed conditions also influenced ($p \leq 0.05$) the hectoliter weight of durum wheat; however, in the irrigated production system, this parameter was not significantly influenced ($p > 0.05$) (Table 2.12).

The hectoliter weights of the tested cultivars ranged from 31.5 kg/hl to 48.9 kg/hl under rain-fed conditions and from 59.3 kg/hl to 81.6 kg/hl under irrigated production systems (Table 2.13). The *Donmateo*, *Mangudo*, and *Tate* cultivars showed the highest hectoliter weights in the rain-fed production system, while the *Tate* and *Mangudo* cultivars recorded the highest hectoliter weights in the irrigated production system. In contrast, the *Bakalcha* and *Bullalla* cultivars recorded the lowest hectoliter weights in both production systems (Table 2.13). The variation in hectoliter weight among the cultivars in both production systems may be attributed to their genetic factors, which is supported by the findings of Szuba *et al.* (2024), indicating that genetic makeup influences chemical composition, nutritional value, and hectoliter weight.

The pair-wise T-test analysis demonstrated that the irrigated production system increased the hectoliter weight of durum wheat by 65.1% compared to the rain-fed production system (Table 2.14). This increase could be due to the optimal soil moisture content and elevated average temperatures that prevailed in the irrigated production system, leading to enhanced grain filling and increased hectoliter weight compared to the rain-fed system. In this regard, previous studies have indicated that the hectoliter weight of wheat is influenced by several factors, including the physical properties of grain (shape and size) and environmental conditions, particularly the amount of moisture in the soil and the temperatures during the growing season of the crop (Panghal *et al.*, 2019; Marinciu *et al.*, 2021).

Table 2.12. Mean square values for same grain quality parameters of durum wheat cultivars under rain-fed and irrigated production systems (data combined over the 2020 and 2021 cropping years)

Source of variation	D.F	Rain-fed production system				Irrigation production system			
		TKW (g)	HLW (kg/hl)	SC (%)	PC (%)	TKW (g)	HLW (kg/hl)	SC (%)	PC (%)
Year (Y)	1	61.8**	19.04*	5.08 ^{ns}	0.06 ^{ns}	21.68 ^{ns}	10.44 ^{ns}	0.51 ^{ns}	0.19 ^{ns}
Cultivar (C)	19	403**	202**	7.01*	7.4**	88.50*	267.5*	21.1**	10.9*
Y*C	19	11.0**	2.00*	0.57 ^{ns}	0.01 ^{ns}	0.49 ^{ns}	1.15 ^{ns}	0.06 ^{ns}	0.01 ^{ns}
Error	78	9.83	7.90	4.64	0.43	22.33	11.52	4.81	0.50
Grand mean		34.56	41.78	69.28	13.29	46.11	68.98	66.74	11.99
CV (%)		9.07	6.74	3.11	4.95	10.25	4.94	3.29	5.90
DMRT (5%)		6.63	5.96	2.47	1.39	9.99	7.20	2.52	1.49

ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. D.F= Degree of freedom, TKW (g) =Thousand kernel weight in gram, HLW (kg/hl) = Hectoliter weight (kg/hl), SC (%) = Starch content (%), PC (%) = Protein content (%), Y*C = Combined effect of year with cultivar, DMRT (5%) = Duncan's multiple range test at 5 percent, and CV (%) = Percentage of coefficient of variation.

Table 2.13. Grain quality response of durum wheat cultivars under rain-fed and irrigated production systems (data combined over the 2020 and 2021 cropping years)

Cultivars	Rain-fed production system				Irrigation production system			
	Thousand kernel weight(g)	Hectoliter weight(kg/hl)	Starch content (%)	Protein content (%)	Thousand kernel weight (g)	Hectoliter weight (kg/hl)	Starch content (%)	Protein content (%)
<i>Alemtena</i>	42.0 ^{a-c}	46.7 ^{a-c}	67.0 ^{c-f}	13.4 ^{b-g}	47.8 ^{a-c}	72.0 ^{c-g}	69.7 ^{a-e}	11.1 ^{c-e}
<i>Bakalcha</i>	26.5 ^{hi}	31.5 ^g	64.1 ^h	14.9 ^a	38.5 ^c	59.8 ^j	67.8 ^{de}	13.6 ^a
<i>Bullalla</i>	28.5 ^{f-i}	34.1 ^{fg}	64.2 ^{gh}	14.5 ^{a-c}	38.5 ^c	59.3 ^j	67.7 ^e	13.5 ^a
<i>Denbi</i>	24.0 ⁱ	36.6 ^{e-g}	65.3 ^{e-h}	13.6 ^{a-g}	45.2 ^{a-c}	60.5 ^j	68.5 ^{c-e}	12.9 ^{ab}
<i>Dire</i>	30.5 ^{f-i}	44.2 ^{a-d}	65.5 ^{e-h}	14.3 ^{a-d}	45.9 ^{a-c}	67.8 ^{d-i}	68.8 ^{b-e}	12.6 ^{ab}
<i>Donmateo</i>	41.0 ^{b-d}	48.9 ^a	67.1 ^{c-f}	13.2 ^{c-g}	46.4 ^{a-c}	71.5 ^{c-g}	69.6 ^{a-e}	10.7 ^{de}
<i>Ejersa</i>	45.0 ^{a-c}	44.4 ^{a-d}	66.7 ^{c-g}	13.4 ^{b-g}	46.9 ^{a-c}	66.4 ^{e-j}	68.9 ^{b-e}	12.5 ^{a-c}
<i>Fetan</i>	24.5 ⁱ	34.8 ^{fg}	65.1 ^{e-h}	14.2 ^{a-e}	45.9 ^{a-c}	63.9 ^{h-j}	68.4 ^{c-e}	13.5 ^a
<i>Gerardo</i>	33.3 ^{e-g}	32.9 ^{fg}	66.3 ^{d-h}	13.0 ^{d-g}	42.5 ^{a-c}	63.3 ^{ij}	69.0 ^{a-e}	12.9 ^{ab}
<i>Hitosa</i>	30.5 ^{f-i}	38.7 ^{d-f}	68.7 ^{a-d}	12.4 ^g	50.4 ^{ab}	74.6 ^{a-d}	70.2 ^{a-d}	10.3 ^{de}
<i>Mangudo</i>	48.6 ^a	48.8 ^a	70.0 ^{ab}	10.9 ^h	51.8 ^a	79.4 ^{ab}	71.4 ^a	9.8 ^e
<i>Mokiye</i>	33.5 ^{e-g}	45.6 ^{a-c}	66.8 ^{c-f}	13.6 ^{a-g}	43.9 ^{a-c}	60.4 ^j	68.6 ^{c-e}	11.6 ^{b-d}
<i>Obsa</i>	26.0 ^{hi}	42.2 ^{c-e}	65.7 ^{e-h}	13.7 ^{a-g}	45.5 ^{a-c}	66.0 ^{f-j}	68.6 ^{c-e}	13.1 ^{ab}
<i>Tate</i>	48.3 ^a	48.3 ^{ab}	69.2 ^{a-c}	12.6 ^{fg}	50.5 ^{ab}	81.6 ^a	70.7 ^{a-c}	10.1 ^e
<i>Tesfaye</i>	46.9 ^{ab}	47.5 ^{a-c}	70.1 ^a	10.6 ^h	51.3 ^a	76.6 ^{a-c}	71.3 ^{ab}	9.9 ^e
<i>Toltu</i>	28.8 ^{f-i}	37.9 ^{ef}	64.6 ^{f-h}	14.6 ^{ab}	40.8 ^{bc}	65.5 ^{g-j}	67.9 ^{de}	13.6 ^a
<i>Ude</i>	27.0 ^{g-i}	36.7 ^{e-g}	64.9 ^{f-h}	13.9 ^{a-f}	46.5 ^{a-c}	73.9 ^{b-d}	68.8 ^{b-e}	12.5 ^{a-c}
<i>Utuba</i>	35.0 ^{d-f}	46.3 ^{a-c}	69.0 ^{a-c}	13.7 ^{a-g}	47.5 ^{a-c}	73.0 ^{b-f}	69.8 ^{a-e}	12.7 ^{ab}
<i>Werer</i>	38.8 ^{c-e}	46.9 ^{a-c}	67.5 ^{b-e}	12.7 ^{fg}	49.5 ^{ab}	73.4 ^{b-e}	70.2 ^{a-d}	10.6 ^{de}
<i>Yerer</i>	32.5 ^{e-h}	42.5 ^{b-e}	67.0 ^{c-f}	12.8 ^{e-g}	47.3 ^{a-c}	70.9 ^{c-h}	69.7 ^{a-e}	12.4 ^{a-c}
Grand mean	34.56	41.78	66.74	13.29	46.11	68.98	69.28	11.99
DMRT(5%)	6.63	5.96	2.52	1.39	9.99	7.20	2.47	1.49
CV (%)	9.07	6.74	3.29	4.95	10.25	4.94	3.11	5.90
MSE±	9.83	7.90	4.64	0.43	22.33	11.52	4.81	0.50
LS	**	**	*	**	*	*	**	*

Mean followed by the same letters are non-significant. DMRT (5%) = Duncan's multiple range test at 5 percent, CV (%) = Percentage of coefficient of variation, and LS=Level of significance.

Table 2.14. The pair-wise T-test analysis of same grain quality of durum wheat cultivars under rain-fed and irrigated production systems (data combined over the 2020 and 2021 cropping years)

Parameter	Irrigation	Rain-fed	MD	SD	P-value	T _{test}		L.C.I (95%)	U. C.I (95%)
						T _{cal}	T _{tab}		
TKW (g)	46.1	34.56	11.5	1.1	0.05	10.5	4.3	9.25	13.84
HLW (kg/hl)	68.98	41.78	27.2	0.4	0.05	67.9	4.3	26.36	28.04
SC (%)	69.28	66.74	2.54	0.4	0.02	6.89	4.3	0.95	4.13
PC (%)	11.99	13.29	-1.3	0.3	0.04	-4.4	2.9	-2.59	-0.05

TKW (g) = Thousand kernel weight (g), HLW (kg/hl) = Hectoliter weight (kg/hl), SC (%) = Starch content (%), PC (%) = Protein content (%), MD = Mean difference, SD = Standard deviation, L.C.I= Lower confidential Interval at 95%, U.C.I= Upper confidential Interval at 95%.

Starch content

The pooled data analysis over the two years revealed significant effects of cultivars on the starch content of durum wheat, particularly at $p \leq 0.05$ and $p \leq 0.01$ levels under both rain-fed and irrigated systems. Notably, while the year and the interaction between year and cultivar did not significantly influence starch content, cultivar selection emerged as a critical factor (Table 2.12).

In the irrigated production system, the *Mangudo* cultivar exhibited the highest starch content, which was statistically similar to several others, including *Alemtena*, *Donmateo*, *Gerardo*, *Hitosa*, *Tate*, *Tesfaye*, *Utuba*, *Werer*, and *Yerer* (Table 2.13). Conversely, the *Bullalla* cultivar had the lowest starch content, demonstrating significant differences at the $p \leq 0.01$ level. Under the rain-fed production system, the *Tesfaye* cultivar recorded the highest starch content and showed non-significant differences from *Hitosa*, *Mangudo*, *Tate*, and *Utuba*. Similar to the irrigated conditions, *Bullalla* again had the lowest starch content, this time significant at the $p \leq 0.05$ level (Table 2.13).

These results suggest that cultivars such as *Mangudo* and *Tesfaye*, which showed non-significant differences in starch content compared to other leading cultivars, contribute substantially to grain starch accumulation under both irrigation regimes. This variability can likely be attributed to genetic differences among the cultivars regarding their starch formation capabilities.

Additionally, when comparing starch content across production systems, irrigated crops had a 3.8% increase in starch content compared to those grown in rain-fed conditions (Table 2.14).

This enhancement in starch production under irrigation is likely linked to soil moisture stability during the critical grain-filling period. The findings align with previous research indicating that the carbohydrate content, including starch, in wheat cultivars is influenced by irrigation methods (Singh *et al.*, 2010; Seleiman and Abdel-Aal, 2018). Thus, these results underline the importance of both cultivar selection and irrigation practices in maximizing starch content in durum wheat production.

Protein content

The results of the combined data analysis of variance over the years showed that the cultivar significantly affected the protein content of durum wheat in both rain-fed ($p \leq 0.01$) and irrigated ($p \leq 0.05$) production systems. However, the cropping year and its interaction with the cultivar did not influence ($p > 0.05$) the protein content of durum wheat in either production system (Table 2.13).

The protein content of the tested cultivars under the rain-fed and irrigated production systems ranged from 10.9% to 14.9% and 9.8% to 13.6%, respectively. The *Bakalcha*, *Toltu*, *Bullalla*, and *Fetan* cultivars recorded the highest protein content in both production systems, with protein contents that were statistically similar when compared to one another within each production system (Table 2.13). In contrast, the *Mangudo* and *Tesfaye* cultivars recorded the lowest protein content in both production systems.

Protein content is one of the most important quality parameters of wheat. Cultivars vary in their protein content based on their genetic makeup (Ullah *et al.*, 2020). The variations in protein content among durum wheat cultivars observed in the present study could therefore be associated with the genetic variability of the crops. In this regard, Gadisa and Dugasa (2021) also noted differences in protein content among wheat cultivars.

The results of the combined pair-wise T-test analysis revealed that the grain protein content of durum wheat in the rain-fed production system was 13.29%, while it was 12.99% in the irrigated production system (Table 2.14). As a result, when comparing grain protein content across production systems, rain-fed production system had increased by 10.8% compared to irrigated production system (Table 2.14). According to Aydođan and Soylu (2017), the grain protein content of wheat ranges from 12.62% to 14.16% in rain-fed systems and from 11.53% to 13.85% in irrigated systems, which aligns with the results of the present study. Water

stress during the grain filling stage decreased grain yield but improved the grain protein content of wheat (Javed *et al.*, 2022). Liu *et al.* (2024) also reported that proper management of soil moisture content during the grain filling period is one of the mechanisms to improve wheat grain yield. Khan *et al.* (2020) stated that wheat crops require 350 to 500 mm of rainfall annually, particularly during the grain filling stage. The current research indicated that the grain filling stage of the tested cultivars occurred in October for the rain-fed system and in January for the irrigated system. However, in October, an average monthly rainfall of 45.2 mm was recorded during the tested years, while in January, 142.5 mm of irrigation water was applied artificially (Table 1.2). As a result, low water stress was registered during the grain filling stage of wheat in the rain-fed production system; this led to a reduced grain yield but an increased grain protein content of the tested cultivars compared to the irrigated production system. Previous studies also indicated that the protein content of wheat increased due to low water stress (Kettani *et al.*, 2023).

Gluten contents

The analysis of variance for combined data over the two years revealed that cultivar significantly impacts both wet and dry gluten contents of durum wheat, specifically within rain-fed and irrigated production systems. This significance was observed at the $p \leq 0.01$ level for wet gluten and at the $p \leq 0.05$ level for dry gluten. In contrast, the year factor and the interaction between year and cultivar did not significantly affect either gluten content at the $p > 0.05$ level in both production systems (Table 2.15).

Examining the results under the rain-fed production system, specific cultivars exhibited distinct gluten content values. The *Mangudo* and *Tesfaye* cultivars presented the lowest wet and dry gluten contents, respectively, while only the *Bakalcha* cultivar had the highest wet gluten content. But, both *Bakalcha* and *Toltu* cultivars achieved the maximum dry gluten content. Notably, the wet gluten content of *Bakalcha* exceeded that of *Mangudo* by 43.3%, and the dry gluten contents of *Bakalcha* and *Toltu* were 58.6% and 56.8% higher than that of *Tesfaye*, respectively.

These findings indicate that *Bakalcha* consistently performed best in terms of gluten content across the rain-fed production system, showing significant differences from nearly all other cultivars tested, except for a few like *Bullalla*, *Dire*, *Fetan*, *Toltu*, *Ude*, and *Utuba*. Conversely, *Mangudo* had the lowest gluten values but did not differ significantly from

several cultivars regarding wet gluten. However, it stood out in dry gluten content, demonstrating significant distinctions from most cultivars except for *Geraredo*, *Hitosa*, *Tate*, *Tesfaye*, *Werer*, and *Yerer* (Table 2.16).

This emphasizes the considerable effect of cultivar selection on gluten content, likely attributed to the genetic variability of the cultivars. Supporting literature aligns with these findings, suggesting that genetic factors influence gluten contents in wheat (Ronga *et al.*, 2020; Sułek *et al.*, 2023).

Additionally, a pairwise T-test analysis demonstrated that the rain-fed production system yielded higher gluten contents. Specifically, wet gluten content was 10.3% higher, and dry gluten content was 18.9% higher under rain-fed conditions compared to irrigated systems (Table 2.17). This outcome suggests that the increase in gluten content under rain-fed conditions may stem from soil moisture stress experienced during the grain-filling stage. Previous studies support this phenomenon, indicating that water stress during this critical growth phase can enhance wheat gluten content (Rao *et al.*, 2021).

Table 2.15. Mean square values for same grain quality parameters of durum wheat cultivars under rain-fed and irrigated production systems (data combined over the 2020 and 2021 cropping years)

Source of variation	D.F	Rain-fed production system				Irrigation production system			
		WGC (%)	DGC (%)	GI (%)	SDS (ml)	WGC (%)	DGC (%)	GI (%)	SDS (ml)
Year (Y)	1	0.27 ^{ns}	0.35 ^{ns}	14.15 ^{ns}	1.72 ^{ns}	26.69 ^{ns}	0.12 ^{ns}	14.15 ^{ns}	7.35 ^{ns}
Cultivar (C)	19	91.84 ^{**}	27.49 ^{**}	364.94 ^{**}	91.97 ^{**}	21.21 [*]	12.03 [*]	364.94 ^{**}	45.79 [*]
Y*C	19	0.01 ^{ns}	0.01 ^{ns}	2.88 ^{ns}	0.14 ^{ns}	0.30 ^{ns}	0.09 ^{ns}	2.88 ^{ns}	0.43 ^{ns}
Error	78	8.22	1.19	27.35	8.33	2.31	0.25	27.35	4.65
Grand mean		36.53	14.42	84.05	42.57	33.11	12.13	84.05	39.27
CV (%)		7.85	7.57	6.22	6.78	4.59	4.09	6.01	5.49
DMRT (5%)		6.06	2.31	6.01	3.32	3.17	1.08	6.22	4.56

ns, *and **, non-significant, significant and highly significant at $p > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. D.F= Degree of freedom, Y*C = Combined effect of year with cultivar, DMRT (5%) = Duncan's multiple range test at 5 percent, CV (%) = Percentage of coefficient of variation, WGC= Wet gluten content (%), DGC= Dry gluten content (%), GI= Gluten index (%) and SDSS-Sediment (ml)

Gluten index

The analysis of variance from two years of data has revealed significant differences in the gluten index of durum wheat cultivars, particularly regarding cultivar selection ($p \leq 0.01$). In

contrast, the year and the interaction between year and cultivar did not significantly affect the gluten index at a threshold of $p > 0.05$ in both irrigated and rain-fed systems (Table 2.15).

In the irrigated production system, the gluten index varied between 71.1% and 94.3%. The cultivars exhibited notable differences, with *Mangudo* showing the lowest gluten index and *Bakalcha* demonstrating the highest gluten index at statistically significant levels ($p \leq 0.01$), as illustrated in Table 2.16. Similarly, in the rain-fed production system, gluten index values ranged from 73% to 96.5%, again highlighting *Bakalcha* as the highest performer and *Mangudo* as the lowest ($p \leq 0.01$).

These findings underscore the genetic differences among cultivars, particularly the fact that the *Bakalcha* cultivar consistently produced the highest gluten index, regardless of the production system. This observation aligns with previous research conducted by Vida *et al.* (2014), which found significant genetic influence on the gluten index.

Further investigation into the impact of production systems on the gluten index revealed that the rain-fed system increased by 4.5 gluten index percentage that was compared to the irrigated system (Table 2.17), suggesting that the environmental conditions which was recorded in the rain-fed production system more suitable for gluten index production and also can influence gluten index characteristics. This finding is consistent with other studies that have reported the effect of environmental variables on the gluten index (Fois *et al.*, 2011). Moreover, Gagliardi *et al.* (2020) indicated that factors such as genotype, growing season, and nitrogen availability also play crucial roles in determining durum wheat gluten protein levels.

The gluten index, defined as the percentage of gluten that remains on a sieve (Podolska *et al.*, 2020), serves as an important indicator of gluten strength and elasticity. Values above 80% indicate strong gluten, while those below 50% signify very soft gluten and the softest gluten index was the better seed quality for food processing (Tiefenbacher, 2017). Overall, this study provides evidence that both cultivar choice and production system significantly impact the gluten index, which is essential for assessing the quality and usability of durum wheat in food products.

Sodium dodecyl sulfate (SDS)-sedimentation volume

The results of the two year combined data analysis exhibited that cultivars are significantly affected the SDS sedimentation in both irrigated and rain-fed production systems, with p-values of ≤ 0.01 and 0.05 , respectively. In contrast, the main effect of the year and the interaction effect of year and cultivar had no significant impact on the SDS sedimentation at $p > 0.05$ (Table 2.15).

The results of the combined data analysis indicated that, during the irrigated growing season, SDS sedimentation ranged from 35.6 to 44 ml, with the lowest SDS sedimentation observed in the *Mangudo* cultivar and the highest recorded for the *Bakalcha* cultivar (Table 2.16). Conversely, under the rain-fed growing season, the combined analysis revealed that the SDS sedimentation volume ranged from 36.2 to 47.5 ml. During this season, the smallest SDS sedimentation was registered in the *Mangudo* cultivar, which was significantly different from all tested cultivars except for *Hitosa*, *Tate*, *Tesfaye*, and *Werer*. Similarly, the highest SDS sedimentation volume was recorded for the *Bakalcha* cultivar, which showed no significant difference from *Bullalla*, *Denbi*, *Fetan*, *Mokuye*, *Toltu*, *Ude*, and *Utuba* cultivars (Table 2.16).

Both irrigated and rain-fed production systems indicated that the *Bakalcha* cultivar increased the SDS sedimentation volume more than the other tested cultivars, likely due to the genetic differences among them. The previous findings also indicated that SDSS (ml) and protein content were influenced by the genetic factors of the cultivars (Würschum *et al.*, 2016).

The pair-wise T-test analysis of SDS sedimentation between irrigated and rain-fed production systems showed that the rain-fed system increased the percentage of SDS sedimentation by 8.4% compared to the irrigated production system (Table 2.17). This result indicates that the SDS sedimentation of durum wheat cultivars was also affected by the growing seasons in which they were planted. In this regard, previous research has also shown that the production system influences the sodium dodecyl sulfate sedimentation volume of wheat cultivars (Silva *et al.*, 2019).

Table 2.16. Same grain quality response of durum wheat cultivars under rain-fed and irrigated production systems (data combined over the 2020 and 2021 cropping years)

Cultivars	Rain-fed production system				Irrigation production system			
	Wet gluten content (%)	Dry gluten content (%)	Gluten index (%)	SDSS-Sediment (ml)	Wet gluten content (%)	Dry gluten content (%)	Gluten index (%)	SDSS-Sediment(ml)
<i>Alemtena</i>	35.7 ^{c-g}	13.8 ^{d-f}	81 ^{d-h}	41.0 ^{e-g}	32.2 ^{c-h}	11.4 ^{g-j}	80.3 ^{b-e}	37.8 ^{c-g}
<i>Bakalcha</i>	44.0 ^a	17.6 ^a	96.5 ^a	47.5 ^a	35.1 ^{a-c}	14.4 ^a	94.3 ^a	44 ^a
<i>Bullalla</i>	40.5 ^{a-c}	16.9 ^{ab}	95 ^{a-c}	47.2 ^{ab}	35.3 ^{a-c}	14.3 ^a	92.5 ^a	43.4 ^{ab}
<i>Denbi</i>	36.4 ^{c-g}	14.5 ^{c-e}	95 ^{a-c}	47.0 ^{ab}	34.7 ^{a-d}	12.9 ^{b-e}	85.8 ^{a-c}	40.9 ^{a-e}
<i>Dire</i>	40.2 ^{a-d}	16.7 ^{a-c}	86 ^{a-f}	44.1 ^{b-e}	33.3 ^{a-f}	12.3 ^{d-g}	78.3 ^{b-e}	38.4 ^{c-g}
<i>Donmateo</i>	35.2 ^{c-g}	13.4 ^{d-g}	78 ^{f-h}	41.0 ^{e-g}	32.6 ^{b-g}	11.2 ^{h-k}	76.3 ^{c-e}	37.3 ^{d-g}
<i>Ejersa</i>	35.3 ^{c-g}	13.6 ^{d-f}	82 ^{d-h}	42.0 ^{d-f}	33.1 ^{a-f}	11.8 ^{f-i}	79.8 ^{b-e}	42 ^{a-c}
<i>Fetan</i>	40.1 ^{a-e}	16.6 ^{a-c}	90 ^{a-e}	46.0 ^{a-c}	35.9 ^a	13.9 ^{ab}	89.7 ^{ab}	39.2 ^{b-g}
<i>Gerardo</i>	34.9 ^{c-g}	13.2 ^{d-h}	83 ^{d-h}	43.0 ^{c-e}	34.4 ^{a-d}	13.1 ^{b-d}	82.8 ^{a-d}	42.1 ^{a-c}
<i>Hitosa</i>	31.4 ^{fg}	11.8 ^{f-h}	74.7 ^{gh}	37.1 ^h	30.9 ^{e-h}	10.7 ^{i-l}	73.4 ^{de}	36.4 ^{e-g}
<i>Mangudo</i>	30.7 ^g	11.2 ^{gh}	73 ^h	36.2 ^h	29.3 ^h	9.9 ^l	71.1 ^e	35.6 ^g
<i>Mokiye</i>	36.9 ^{b-f}	14.9 ^{b-e}	85 ^{b-g}	45.0 ^{a-d}	33.5 ^{a-f}	11.5 ^{g-j}	78.2 ^{b-e}	39.1 ^{b-g}
<i>Obsa</i>	36.7 ^{b-g}	15.1 ^{b-d}	84.3 ^{c-g}	44.0 ^{b-e}	33.9 ^{a-e}	13.4 ^{a-c}	78.5 ^{b-e}	41.3 ^{a-d}
<i>Tate</i>	31.3 ^{fg}	12.2 ^{f-h}	74 ^{gh}	37.7 ^{gh}	30.5 ^{f-h}	10.4 ^{j-l}	70 ^e	35.8 ^{fg}
<i>Tesfaye</i>	30.9 ^{fg}	11.1 ^h	75 ^{f-h}	36.8 ^h	29.8 ^{gh}	10.3 ^{kl}	74.6 ^{c-e}	35.8 ^{fg}
<i>Toltu</i>	42.7 ^{ab}	17.4 ^a	95.5 ^{ab}	47.0 ^{ab}	35.7 ^{ab}	14.3 ^a	92.3 ^a	43.5 ^{ab}
<i>Ude</i>	40.0 ^{a-e}	16.4 ^{a-c}	92 ^{a-d}	45.9 ^{a-c}	33.8 ^{a-e}	12.0 ^{e-h}	77.7 ^{c-e}	38.8 ^{c-g}
<i>Utuba</i>	38.9 ^{a-e}	16.3 ^{a-c}	85 ^{b-g}	45.5 ^{a-c}	33.6 ^{a-f}	12.7 ^{c-f}	79 ^{b-e}	40.2 ^{a-f}
<i>Werer</i>	34.1 ^{e-g}	12.6 ^{e-h}	76 ^{f-h}	38.0 ^{gh}	31.8 ^{d-h}	10.8 ^{i-l}	75.5 ^{c-e}	36.3 ^{fg}
<i>Yerer</i>	34.4 ^{d-g}	12.7 ^{d-h}	80 ^{e-h}	39.3 ^{f-h}	32.8 ^{a-g}	11.7 ^{f-i}	78.3 ^{b-e}	37.9 ^{c-g}
Grand mean	36.53	14.42	84.05	42.57	33.11	12.13	80.45	39.27
DMRT (5%)	6.06	2.31	11.06	3.32	3.17	1.08	11.57	4.56
CV (%)	7.85	7.57	6.22	6.78	4.59	4.09	6.80	5.49
MSE±	8.22	1.19	27.35	8.33	2.31	0.25	27.35	4.65
LS	**	**	**	**	*	*	**	*

Mean followed by the same letters are non-significant. DMRT (5%) = Duncan's multiple range test at 5 percent, CV (%) = Percentage of coefficient of variation, and LS=Level of significance.

Table 2.17. The pair-wise T-test analysis of same grain quality of durum wheat cultivars under rain-fed and irrigated production systems (data combined over the 2020 and 2021 cropping years)

Parameter	Irrigation	Rain-fed	MD	SD	P-value	T _{test}		L.C.I (95%)	U. C.I (95%)
						T _{cal}	T _{tab}		
WGC (%)	33.11	36.53	3.42	0.48	0.005	-7.2	1.9	-4.42	-2.43
DGC (%)	12.13	14.42	2.29	0.17	0.005	-13.3	4.3	-2.65	-1.93
GI (%)	80.45	84.05	3.6	0.53	0.02	-6.86	4.3	-5.86	-1.34
SDSS (ml)	39.27	42.57	3.3	0.25	0.005	-13.4	9.9	-4.36	-2.23

SDSS=Sodium dodecyl Sulfate-Sedimentation, WGC (%) = Wet gluten content (%), DGC (%) = Dry gluten content (%), GI (%) = Gluten index (%), SDSS (ml) = Sodium dodecyl sulfate (SDS)-sedimentation volume (ml), MD=Mean difference, SD= Standard deviation, L.C.I= Lower confidential Interval at 95%, U.C.I= Upper confidential Interval at 95%.

2.4. CONCLUSION

The analysis of data collected over two years showed that, in a rain-fed production system, the cultivars *Mangudo*, *Tesfaye*, *Utuba*, *Tate*, and *Hitosa* achieved the highest grain yields per hectare, with no notable differences among them. On the other hand, the cultivars *Bakalcha*, *Toltu*, *Bullalla*, *Fetan*, *Ude*, and *Utuba* had the highest protein content, with no significant differences noted. The findings indicated that the cultivar *Utuba* outperformed the other cultivars in both grain yield and protein content in the rain-fed system.

In the irrigated production system, the cultivars *Tesfaye*, *Mangudo*, *Utuba*, *Tate*, and *Hitosa* also showed the highest grain yields, without significant differences among them. Similarly, *Bakalcha*, *Toltu*, *Bullalla*, *Fetan*, *Obsa*, and *Utuba* had the highest protein content, with no significant differences. Under irrigation, *Utuba* again demonstrated superior grain yield and protein content compared to the other cultivars. Thus, *Utuba* is recommended for local farmers and those in comparable agro-climatic ecology, as it offers higher grain yields and good protein content in both rain-fed and irrigated systems.

The advantages of the different production systems were assessed using pairwise T-test analysis. This analysis revealed that the rain-fed system resulted in increased grain protein content and longer emergence times, but it reduced the number of productive tillers, spikelets per spike, kernels per spike, grain yield, biomass yield, thousand kernel weight, and hectoliter weight compared to the irrigated system. In contrast, the irrigated system enhanced the number of productive tillers, spikelets per spike, kernels per spike, grain yield, biomass yield, thousand kernel weight, and hectoliter weight, while decreasing the days to emergence and grain protein content. Therefore, the irrigated production system is preferred for durum wheat grain production, while the rain-fed system may be suitable for producing durum wheat with a focus on grain quality in this area and similar climates

2.5. REFERENCES

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3. EFFECTS OF NITROGEN FERTILIZER RATES ON YIELD, GRAIN QUALITY AND NITROGEN USE EFFICIENCY OF DURUM WHEAT (*Triticum turgidum* L.) CULTIVARS AT DEBRE ZEIT, CENTRAL ETHIOPIA

ABSTRACT

The application of an appropriate nitrogen rate is one of the best methods to save nitrogen fertilizer and reduce production costs in Ethiopia. So far, fertilizer rate recommendations have not been tailored to specific cultivars, and the same rates have been applied to all cultivars. Field experiments were conducted over two years, in 2022 and 2023, on heavy black soil to investigate the effects of nitrogen fertilizer rates on durum wheat growth, yield, and quality in the central part of Ethiopia. The treatments in the experiments consisted of five nitrogen rates (0, 46, 92, 138, and 184 kg N ha⁻¹) and two durum wheat cultivars (Mangudo and Utuba). The experiments were conducted using a randomized complete block design in a factorial arrangement with three replications. The results showed that increasing nitrogen rates from 0 to 138 kg N ha⁻¹ enhanced all the studied parameters, except starch content. Mangudo and Utuba cultivars produced the highest yield and quality, respectively, in response to nitrogen treatments. The yield and quality of the both tested cultivars increased with higher nitrogen rates, with maximum values recorded at 184 kg N ha⁻¹. However, the cost-benefit analysis indicated that 92 kg N ha⁻¹ offered the highest marginal rate of return compared to other nitrogen treatments for both cultivars. Conversely, for each birr invested in Mangudo production, the farmer can expect to recover the one birr invested plus an additional return of 10.1 birr, compared to Utuba production. Consequently, the application of 92 kg N ha⁻¹ is recommended for durum wheat production in the study area and in regions with similar agro-climatic conditions.

Key words: *Cost-benefit, Cultivar; Nitrogen; Protein content; Starch content*

3.1. INTRODUCTION

Durum (*Triticum turgidum* L.) and bread wheat (*Triticum aestivum* L.) species are cultivated worldwide (Blanco, 2024). However, durum wheat production accounts for only 8% of the total wheat production area globally (Ceglar *et al.*, 2021). Of the total area cultivated with durum wheat, 75% is located in Mediterranean countries (Mansouri *et al.*, 2018). Additionally, durum wheat is grown in semi-arid regions such as North Africa, Southern Europe, and the Middle East (Hammami and Sissons, 2020).

In Ethiopia, both durum and bread wheat are cultivated under a rain-fed production system (Wuletaw *et al.*, 2022). Approximately 4.62 million households produce both wheat varieties across an estimated land area of 1.7 million hectares (Kefyalew *et al.*, 2021). Durum wheat is predominantly cultivated in the central, northwestern, and northeastern regions of the country (Meseret *et al.*, 2020). However, durum wheat production accounts for only 5% to 10% of the total wheat cultivated land in Ethiopia (Global Agricultural Information Net work (GAIN), 2018). Yet, Ethiopia encompasses 90% of the 630,000 hectares of land cultivated with durum wheat in Sub-Saharan Africa (Abate and Walegn, 2023). Nonetheless, the national average yield of durum wheat in Ethiopia is below 2.2 t ha⁻¹ (Mekuria *et al.*, 2018). Durum wheat grain serves dual purposes, contributing to food security and providing raw material for the small food processing industry in the country (Sissons, 2022).

Durum wheat grain is a source of various nutrients (Alzuwaid *et al.*, 2021). The nutritional value of durum wheat grain and its production are influenced by several factors, including genotype, growing environments, crop management practices, and their interactions (Božek *et al.*, 2022; Li, *et al.*, 2022; Mancinelli *et al.*, 2023). While durum wheat grain serves primarily as a raw material for pasta production, it is also used in making bread, couscous, pizza, and other products (Ruisi *et al.*, 2021). Durum wheat grain is known to produce high-quality pasta (Banach *et al.*, 2021). According to the international standards for high-quality pasta, it should exhibit a vitreous appearance in cross-section, a golden-amber color, and a distinctive taste and aroma both before and after cooking, and it should not be brittle or easily breakable (Zuk-Gołaszewska *et al.*, 2016).

Among the factors affecting durum wheat grain quality and production, a lack of awareness regarding to nitrogen (N) fertilization recommendation and other technology such as time and method of application. Nitrogen is a crucial macronutrient for crop production and increases

the protein content of wheat grain (De-Santis *et al.*, 2020; Wang *et al.*, 2022; Chakwizira *et al.*, 2023). Thus, the rate, type, and timing of nitrogen fertilizer application are vital for enhancing wheat yield and grain quality (Školníková *et al.*, 2022; Rafiq *et al.*, 2023). The amount of nitrogen fertilizer applied depends on rainfall and its distribution in the soil, which subsequently affects wheat production and grain quality (Boulelouah *et al.*, 2022).

Of the total amount of applied nitrogen fertilizer, only 33% remains available in the soil, while the rest is lost through volatilization, leaching, and denitrification, directly impacting the nitrogen use efficiency of crops (Mălinaş *et al.*, 2022; Govindasamy *et al.*, 2023). Furthermore, nitrogen fertilizer use efficiency is also influenced by soil characteristics of the cultivated crop and the growth environment (Li, *et al.*, 2022). To enhance nitrogen use efficiency and reduce nitrogen losses from cropland, it is essential to harmonize nitrogen fertilizer application with optimal timing (Souissi *et al.*, 2018).

The effect of nitrogen on wheat production has been examined in several studies (Bekalu and Mamo, 2016; Chibsa *et al.*, 2017; Fresew *et al.*, 2018; Dereje *et al.*, 2019; Girma *et al.*, 2021; Megersa *et al.*, 2022; Alemayehu *et al.*, 2023; Workat *et al.*, 2024). The collective findings of these studies indicate that updating the quantity, timing, and method of nitrogen application is essential for optimizing wheat production in Ethiopia. The researchers recommend reviewing and adjusting nitrogen management practices based on insights gained from this body of work conducted over the past several years throughout the country. Therefore, the primary constraints and challenges to improving the production and grain quality of durum wheat in the study area include the lack of timely, updated recommended fertility rates, particularly for nitrogen fertilizer within the rain-fed production system. Consequently, it is critical to update the recommended nitrogen fertilizer rate for improved cultivars to enhance durum wheat production, productivity, and grain quality.

In this study, we hypothesize that applying nitrogen fertilizer at optimal rates could enhance the growth, yield components, yield, and grain quality of durum wheat at the Debre Zeit Research Center in central Ethiopia. The specific objectives of this study are to:

- i) To evaluate nitrogen use efficiencies of *Mangudo* and *Utuba* cultivars
- ii) To assess the effects of different nitrogen fertilizer rates on yield and grain quality of *Mangudo* and *Utuba* cultivars.

3.2. MATERIALS AND METHODS

3.2.1. Description of the Study Area

Please refer the description of the study area from subsection 1.11 (Page 32).

3.2.2. Treatments and Experimental Design

The treatments consisted of two improved durum wheat cultivars (*Mangudo* and *Utuba*) and five nitrogen fertilizer rates (0, 46, 92, 138, and 184 kg N ha⁻¹), which were evaluated at the Debre Zeit Agricultural Research Center in Central Ethiopia for two consecutive cropping seasons during 2022 and 2023. The tested cultivars were selected based on previous research results from rain-fed and irrigated production systems evaluated during 2020 and 2021 G.C. They were chosen for their high yield potential, producing grain yields ranging between 3.5 and 6.5 t ha⁻¹ during the release period under the research field (see Table 3.1). The experiment was designed using a Randomized Complete Block Design (RCBD) with three replicates. Each plot measured 3 m in length and 2 m in width (6 m²), with 0.5 m and 1 m separating plots and blocks, respectively. Each plot comprised ten rows, spaced 20 cm apart. Each cultivar was randomly assigned to each plot.

Table 3.1. Description of the two improved durum wheat cultivars used in the experiment

S/N	Cultivar	Year	Altitude (m above sea level)	Yield (kg ha ⁻¹)	Maintaining centers
1	<i>Mangudo</i>	2012	1800–2650	4925	SARC
2	<i>Utuba</i>	2015	1800–2650	4560	DZARC

DZARC = DebreZeit Agricultural Research Center and SARC = Sinana Agricultural Research Center.

3.2.3. Experimental Procedures and Management

The experimental plots were ploughed using a tractor, and the plots were prepared manually. The seeds of the tested durum wheat cultivars were planted at a rate of 125 kg per hectare using a hand drill at the spacing of 20 cm at a depth of 10 cm and then covered with soil. All recommended TSP (Triple Super Phosphate) fertilizer (100 kg ha⁻¹) was applied by banding the granules at the time of planting. Nitrogen fertilizer was applied at rates of 0, 46, 92, 138, and 184 kg N ha⁻¹ in two splits, using urea as the source of nitrogen. The split application of urea was structured so that 2/3 was applied at tiller initiation, with the remaining 1/3 applied at the booting stage for all fertilizer rates. Urea was applied by slightly opening the soil and covering the fertilizer to minimize loss through volatilization. The planting dates for the experiments were July 16, 2022, and July 15, 2023, respectively. In the experiments, weeds

were controlled through hand weeding, while diseases and insects were managed through chemical applications. Harvesting was performed manually. The grain quality of the tested cultivars was evaluated at the Kulumsa Agricultural Research Centre laboratory, and the procedures used during quality analysis are detailed in the data collection section.

3.2.4. Data Collection and Measurement

3.2.4.1. Phenology, growth, yield related, yield and grain quality parameters

The data collection and measurement for phenology and growth, yield and yield related and grain quality parameters please refer from subsection 2.2.5 (Page 45).

3.2.4.2. Nitrogen use and utilization efficiency

Nitrogen-use efficiency (NUE): It was defined as a ratio of grain yield (Gy) to N-fertilizer supply (Na) (Rawal *et al.*, 2022).

$$NUE = \frac{Gy}{Na}$$

Agronomic efficiency (AE): It was calculated as the ratio of grain yield under fertilizer (Gf) - grain yield under unfertilized (Gu) to quantity of nutrient applied (Na) (Ray *et al.*, 2018; Sarkar *et al.*, 2021).

$$AE = \frac{Gf - Gu}{Na}$$

Physiological efficiency (PE): It was determined as the ratio of the total biological yield (grain + straw) of the fertilized plot (Yf) - total biological yield (grain + straw) of the unfertilized plot (Yu) to Nutrient accumulation of grain and straw in the fertilized plot (Nf) - Nutrient accumulation of grain and straw in the unfertilized plot (Nu) (Ray *et al.*, 2018; Sarkar *et al.*, 2021).

$$PE = \frac{(Yf - Yu)}{Nf - Nu}$$

Agro physiological efficiency (APE): It was calculated as the ratio of grain yield in the fertilized plot (Gf) - grain yield in the unfertilized plot (Gu) to Nutrient accumulation of grain and straw in the fertilized plot (Nf) - Nutrient accumulation of grain and straw in the unfertilized plot (Nu) (El Berguiet *et al.*, 2020).

$$APE = \frac{(Gf - Gu)}{(Nf - Nu)}$$

Apparent recovery efficiency (ARE): It was determined as the ratio of nutrient accumulation of grain and straw in the fertilized plot (Nf) - Nutrient accumulation of grain and straw in the unfertilized plot (Nu) to quantity of nutrient applied (Na) and multiplied by 100 (Jalpa *et al.*, 2020).

$$ARE = \frac{(Nf - Nu)}{Na} * 100$$

Utilization efficiency (UE): It was calculated the multiplication of Physiological Efficiency (PE) and Apparent Recovery Efficiency (ARE) (De Oliveira *et al.*, 2020). $UE = PE * ARE/100$

3.2.5. Data Analysis

The analyses of variances were carried out using statistical analysis (Gomez and Gomez, 1984) computer software by using Gen-stat software v.19. The yearly homogeneity tests were conducted through the Bartlett test (Gomez and Gomez, 1984). After the experiments homogeneity test was carried out then the combined analysis over the year was done according to Gomez and Gomez (1984). The mean separations within individual parameters were performed using the least significant difference (LSD) at 5% level of significance.

3.2.6. Partial Budget Analysis

Partial budget analysis was carried out for every treatment based on CIMMYT (1988) to indicate the economic superiority of alternative treatments over the control treatment. Fertilizer cost and mean price of wheat (grain and straw) were collected from the districts and cost for grain yield per quintal was 4000 Birr, cost for straw per hundred kilogram was 1000 Birr, and cost for nitrogen fertilizer per quintal is 3500 Birr. The average yield was adjusted downward by 10% from the exact yield to reflect the difference between the experimental yield and yield of farmers. The marginal rate of return (%) was calculated as changes in net benefit divided by changes in cost.

3.3. RESULTS AND DISCUSSION

3.3.1. Impact of Nitrogen Fertilizer Rates on Phenology and Growth Parameters of Durum Wheat Cultivars.

3.3.1.1. Phenology and growth parameters

Population density per meter square

The combined analysis of variance over the two years revealed that population density per square meter was significantly affected by both the main effects of cultivar and nitrogen rates at $p \leq 0.01$, as well as the interaction effect of cultivar with nitrogen rates at $p \leq 0.05$ (Table 3.2).

The data from the combined analysis indicated that the population density per square meter of the tested cultivars, under the interaction effect of cultivar and nitrogen rates, ranged from 77 to 176.5 plants per square meter (Table 3.3). The highest population density per square meter was recorded for the cultivar *Utuba* at a nitrogen application rate of 184 kg N ha⁻¹, while the lowest was recorded for the cultivar *Mangudo* when no nitrogen fertilizer was applied (0 kg N ha⁻¹) (Table 3.3).

The results of the combined analysis over the years also showed that the cultivar *Utuba* achieved the highest population density per square meter at all nitrogen rates compared to the cultivar *Mangudo*. This variation may be attributed to differences in tiller production capacity between the tested cultivars under the same nitrogen rates and cropping years. Conversely, both the cultivars *Utuba* and *Mangudo* exhibited a statistically significant increase in population density per square meter as nitrogen rates increased from 0 to 184 kg N ha⁻¹. Specifically, increasing the nitrogen rate from 0 to 92 kg N ha⁻¹ significantly boosted the population density per square meter of the tested cultivars; however, mathematical increasing in population density for both cultivars at the application of nitrogen rates from 92 to 184 kg N ha⁻¹ but did not show a statistically significant difference between the tested cultivars under the application of 92 to 184 kg N ha⁻¹ (Table 3.3). Consequently, the results of this research indicate that 92 kg N ha⁻¹ is the optimal rate for achieving higher population density per square meter for the tested cultivars, likely due to their specific responsiveness to nitrogen fertilizer. In this context, the current findings of this study align with those of various

scholars who indicated that increasing nitrogen fertilizer rates significantly enhances the population density of wheat (Fernandez *et al.*, 2020; Alemayehu *et al.*, 2023).

Table 3.2. Mean square results for phenology and growth parameters of durum wheat cultivars (combined over 2022 and 2023 cropping years).

Source of variation	Degrees of freedom	Population density per meter square (No)	Days to heading (cm)	Days to maturity (No)	Plant height (cm)
Replication (R)	2	473	0.7	19.1	1.4
Years (Y)	1	714 ^{ns}	0.5 ^{ns}	2.8 ^{ns}	5.5 ^{ns}
Cultivars (C)	1	4183 ^{**}	44.2 [*]	10.4 ^{ns}	232.1 ^{ns}
Nitrogen rate (N)	4	16211 ^{**}	38.6 ^{**}	272.7 ^{**}	510.2 ^{**}
Y*C	1	0.2 [*]	0.1 [*]	0.02 ^{ns}	0.1 ^{ns}
Y*N	4	1.2 [*]	0.05 [*]	0.23 [*]	0.1 [*]
C*N	4	340 [*]	0.5 [*]	2.9 [*]	36.6 [*]
Y*C*N	4	0.3 [*]	0.02 [*]	0.26 [*]	0.1 [*]
Error	38	283.3	6.4	14.8	90.0
Grand mean		129.85	57.81	111.18	84.50
CV (%)		12.96	4.40	3.46	11.23

ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. Y*C= Years and Cultivar interaction, Y*N= Years and Nitrogen interaction, C*N= Cultivar and Nitrogen interaction, Y*C*N= Years, Cultivar, and Nitrogen interaction, CV (%) = Percentage of coefficient of variation.

Days to heading

The two years of the combined analysis revealed that the main effects of cultivar and nitrogen rates on the number of days to heading were significant at $p \leq 0.05$ and $p \leq 0.01$, respectively. However, the interaction between cultivar and nitrogen rates had a significant effect on days to heading at $p \leq 0.05$ (Table 3.2).

The combined analysis of variance over the years indicated that the interaction effect of cultivar and nitrogen rates increased the number of days to heading from 55 to 61 days (Table 3.3). The highest and lowest numbers of days to heading were recorded at 184 kg N ha⁻¹ and 0 kg N ha⁻¹ for the *Mangudo* and *Utuba* cultivars, respectively (Table 3.3). The number of days to heading was delayed when the nitrogen rate was increased from 0 to 184 kg N ha⁻¹ for both tested cultivars. Conversely, the *Mangudo* cultivar headed significantly later ($p \leq 0.05$) compared to the *Utuba* cultivar, which was evaluated under the same nitrogen rates. Consequently, the number of days to heading recorded for the *Mangudo* cultivar was higher than that of the *Utuba* cultivar across all nitrogen fertilizer rates. Thus, the results of this research demonstrated that cultivars exhibited different days to heading when tested under the

same nitrogen rates, likely due to genetic variability in nitrogen use efficiency. Furthermore, previous studies have shown that nitrogen rates significantly affect the number of days to heading in wheat cultivars within the same production system (Gebrel *et al.*, 2020; Almaz *et al.*, 2022).

Table 3.3. The mean result of phenology performance of durum wheat cultivars under nitrogen rates (combined over the 2022 and 2023 cropping years).

Cultivar	Nitrogen rate (kg N ha ⁻¹)	Population density per meter square	Days to heading	Days to physiological maturity	Plant height
<i>Mangudo</i>	0	77 ^f	55.8 ^{ef}	103.5 ^d	74.5 ^d
<i>Mangudo</i>	46	98 ^{de}	57.7 ^{b-e}	108.8 ^{bc}	79.5 ^{cd}
<i>Mangudo</i>	92	141 ^c	58.8 ^{a-d}	112.7 ^{ab}	85.5 ^{a-d}
<i>Mangudo</i>	138	145 ^c	60 ^{ab}	113.5 ^a	87 ^{a-c}
<i>Mangudo</i>	184	146 ^c	60.9 ^a	115 ^a	87.1 ^{a-c}
<i>Utuba</i>	0	82 ^{ef}	54.8 ^f	104.5 ^{cd}	75 ^d
<i>Utuba</i>	46	106.6 ^d	56.5 ^{d-f}	108.5 ^{bc}	80.5 ^{b-d}
<i>Utuba</i>	92	156.5 ^{bc}	57 ^{c-f}	112.9 ^{ab}	89.5 ^{a-c}
<i>Utuba</i>	138	169.5 ^{ab}	58 ^{a-e}	115 ^a	91.5 ^{ab}
<i>Utuba</i>	184	176.5 ^a	59 ^{a-c}	117 ^a	94.5 ^a
Grand mean		129.8	57.86	111.15	84.4
LSD 5%		19.67	2.97	4.5	11.09
CV (%)		12.96	4.4	3.46	11.23
LS		*	*	*	*

Mean followed by the same letter are non-significant. LSD (%) = Listed significant different at 5% level, and CV (%) = Percentage of coefficient of variation, LS=level of significant.

Days to physiological maturity

The combined data analysis of variance over the two years indicated that the main effect of nitrogen rates at $p \leq 0.01$ and the interaction effect of cultivar and nitrogen rate at $p \leq 0.05$ significantly influenced the number of days to physiological maturity of durum wheat (Table 3.2).

Under the tested nitrogen rates, the number of days required for the cultivars to reach physiological maturity ranged from 103.5 to 117 days. The cultivar *Utuba* matured later at a rate of 184 kg N ha⁻¹, while the cultivar *Mangudo* matured earlier at 0 kg N ha⁻¹ (Table 3.3). The results of this research indicate that cultivar *Utuba* required more days to reach physiological maturity compared to cultivar *Mangudo* at any nitrogen fertilizer rate. Increasing of the application of N-rate from 0 to 184 kg ha⁻¹ prolonged the physiological maturity of both tested cultivars. As a result, increasing number of days to grain-filling stage and finally advantageous for grain yield production due to the increasing of grain simulation

period. However, when the physiological maturity is reduced the grain yield of the tested cultivars have been reduced. Therefore, from the current research result *Utuba* cultivars has higher physiological maturity which was expected higher grain yield potential as compared to *Mangudo* cultivar. This difference may be attributed to genetic variability in nitrogen use efficiency among the tested cultivars during the same production years. Generally, a rate of 92 kg N ha⁻¹ was identified as the optimum nitrogen rate for physiological maturity for both cultivars in the same production year. In this context, research findings from various scholars have also reported that increasing nitrogen fertilizer rates prolong the number of days to physiological maturity of wheat cultivars (Dereje, 2022; Gawdiya *et al.*, 2023).

Plant height

The results of the combined data analysis of variance over the two years revealed that the main effect of nitrogen rates, along with its interaction with cultivar, had a significant impact on the plant height of durum wheat cultivars at $p \leq 0.01$ and $p \leq 0.05$, respectively (Table 3.2).

The study found that, under the tested nitrogen rates and cultivars, the plant height of durum wheat ranged from 74.5 cm to 94.5 cm (Table 3.3). The highest plant height was recorded for the cultivar *Utuba* at a nitrogen rate of 184 kg ha⁻¹, while the cultivar *Manguda* exhibited the lowest plant height at 0 nitrogen rates per hectare (Table 3.3). In contrast, the cultivar *Utuba* consistently increased in height at any nitrogen rate applied per hectare, whereas the cultivar *Manguda* only increased in height from 0 to 138 kg N ha⁻¹ (Table 3.3).

These results indicate that the tested cultivars possess different potentials for plant height development under the same nitrogen fertilizer rates, which may be attributed to genetic variability in response to nitrogen fertilizer application. Therefore, the cultivar *Utuba* is genetically predisposed to a greater plant height and has demonstrated a high straw yield, making it more suitable for livestock production in Ethiopia compared to the *Manguda* cultivar. Furthermore, this research finding is supported by previous results from Khan *et al.* (2022), which reported considerable variation in the plant height of different wheat cultivars when grown under varying nitrogen rates. Similarly, Alemayehu *et al.* (2023) also highlighted that differences in plant height are attributable to the nitrogen rates applied during the growing season of wheat.

3.3.2. Effect of Nitrogen Rates on Yield and Yield Related Parameters of Durum Wheat Cultivars.

3.3.2.1. Yield and yield related parameters

Number of productive tillers per plant

The two year of the combined data results showed that number of productive tillers per plant was significantly affected by the interaction of cultivar and N-rates at $p \leq 0.01$ (Table 3.4).

The combined data analysis over two years indicated that *Utuba* recorded the highest number of productive tillers per plant at 184 kg N ha⁻¹, while the both *Mangudo* and *Utuba* recorded the smallest number of productive tillers per plant at 0 kg N ha⁻¹ (Table 3.5). Increasing the nitrogen rate from 0 to 92 kg N ha⁻¹ enhanced the number of productive tillers in the *Mangudo* cultivar, whereas increasing the nitrogen rate from 0 to 184 kg N ha⁻¹ increased the number of productive tillers in the *Utuba* cultivar (Table 3.5). As a result, the cultivar *Utuba* exhibited a higher number of productive tillers at each rate of nitrogen fertilizer compared to the *Mangudo* cultivar, which could be attributed to the genetic variability of the cultivars in response to nitrogen fertilizer. In this regard, previous research also indicated that the genetic characteristics of the cultivars and the nitrogen fertilizer rates affected the number of productive tillers in the wheat crop (Alemayehu *et al.*, 2023; Ararsa, 2023).

Spike length

The combined data analysis of variance over the years showed that the main effects of cultivar ($p \leq 0.05$) and nitrogen rates ($p \leq 0.05$), as well as their interaction ($p \leq 0.01$), had a significant effect on the spike length of durum wheat (Table 3.4).

The analysis indicated that the *Mangudo* cultivar recorded the highest spike length at 184 kg N ha⁻¹, while the *Utuba* cultivar recorded the smallest spike length at 0 kg N ha⁻¹ (Table 3.5). Conversely, increasing the nitrogen rates from 0 to 184 kg ha⁻¹ enhanced the spike length of both tested cultivars (Table 3.5). However, the spike length of the *Mangudo* cultivar was higher at all rates of nitrogen fertilizer compared to that of the *Utuba* cultivar, which was tested under the same nitrogen rates. This difference may be attributed to the genetic variability of the crops responding to nitrogen fertilizer. In this regard, previous research has also indicated that nitrogen fertilizer rates increase the spike length of wheat cultivars (Luo *et al.*, 2021; Ararsa, 2023; El-Dayem *et al.*, 2024).

Table 3.4. Mean square results of yield-components of the durum wheat cultivars combined over 2022 and 2023 cropping years.

Source of variation	Degrees of freedom	Productive tillers/Plant (No)	Spike length (cm)	Number of spikelet/Spike (No)	Number of grain/Spike (No)
Replication (R)	2	1.40	1.27	16.22	16.2
Years (Y)	1	0.6 ^{ns}	0.29 ^{ns}	6.01 ^{ns}	1008.6 ^{ns}
Cultivar (C)	1	38.4 ^{**}	8.07 [*]	22.82 ^{ns}	15.0 ^{ns}
Nitrogen rates (N)	4	55.3 ^{**}	10.21 [*]	107.56 ^{**}	1744.1 ^{**}
Y*C	1	0.0 [*]	0.11 [*]	0.01 ^{ns}	0.6 ^{ns}
Y*N	4	0.1 [*]	0.03 [*]	0.02 ^{ns}	0.1 [*]
C*N	4	8.9 ^{**}	0.25 ^{**}	21.06 [*]	8.5 [*]
Y*C*N	4	0.04 [*]	0.04 [*]	0.01 [*]	0.1 [*]
Error	38	0.2	0.62	3.69	9.2
Grand mean		3.70	6.30	14.88	26.1
CV (%)		13.30	12.54	12.91	11.59

*ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. Y*C= Years and Cultivar interaction, Y*N= Years and Nitrogen interaction, C*N= Cultivar and Nitrogen interaction, Y*C*N= Years, Cultivar, and Nitrogen interaction, CV (%) = Percentage of coefficient of variation.*

Table 3.5. The mean performances for yield-components of durum wheat cultivars over 2022 and 2023 cropping years at DZARC.

Cultivar	Nitrogen rate (kg ha ⁻¹)	Productive tillers/Plant (No)	Spike length (cm)	Number of spikelet/Spike (No)	Number of grains/Spike (No)
<i>Mangudo</i>	0	1f	5.2 ^{de}	11.6 ^{de}	8 ^e
<i>Mangudo</i>	46	1.7e	5.8 ^{c-e}	12.6 ^d	17 ^d
<i>Mangudo</i>	92	3.8d	7.1 ^{ab}	15.5 ^{bc}	32.6 ^{bc}
<i>Mangudo</i>	138	3.8d	7.3 ^{ab}	15.6 ^{bc}	34 ^{bc}
<i>Mangudo</i>	184	4d	7.8 ^a	15.7 ^{bc}	36 ^{ab}
<i>Utuba</i>	0	1f	5.0 ^e	9.6 ^e	9.8 ^e
<i>Utuba</i>	46	2e	5.3 ^{de}	13.7 ^{cd}	18.3 ^d
<i>Utuba</i>	92	4.8c	6.0 ^{cd}	15.6 ^{bc}	31 ^c
<i>Utuba</i>	138	6.8b	6.4 ^{bc}	17.7 ^b	36 ^{ab}
<i>Utuba</i>	184	7.8a	7.0 ^{ab}	20.8 ^a	38 ^a
Grand mean		3.7	6.3	14.88	26.1
LSD 5%		0.61	0.92	2.24	3.53
CV (%)		13.3	12.54	12.91	11.59
LS		**	**	*	*

Mean followed by the same letter are non-significant. LSD (%) = Listed significant different at 5% level, and CV (%) = Percentage of coefficient of variation, LS=level of significant.

Number of spikelet per spike

The combined analysis of variance over two years indicated that the number of spikelets per spike of durum wheat was significantly affected by the interaction effect of cultivar and nitrogen rates, with significance levels of $p \leq 0.05$ (Table 3.4).

The combined data analysis over the years showed that the *Utuba* cultivar registered the highest number of spikelets per spike at 184 kg N ha⁻¹, while the same cultivar recorded the smallest number of spikelets per spike at 0 kg N ha⁻¹ (Table 3.5). In contrast, increasing nitrogen rates from 0 to 184 kg ha⁻¹ led to an increase in the number of spikelets per spike in both cultivars (Table 3.5). Furthermore, the number of spikelets per spike of the *Utuba* cultivar was higher at all nitrogen fertilizer rates, except for the zero nitrogen rate per hectare, compared to the spike length of the *Mangudo* cultivar, which was tested under the same nitrogen rates. This difference may be attributed to the variation in nitrogen use efficiency between the tested cultivars. Supporting this finding, previous research also demonstrated that nitrogen fertilizer rates significantly affected the number of spikelets per spike in wheat cultivars (Liu *et al.*, 2021; Mirzakhani and Dadian, 2024).

Number of grains per spike

The combined data analysis of variance over two years showed that the number of grains per spike was affected by the main effect of nitrogen rates and the interaction effect between cultivars and nitrogen rates at $p \leq 0.01$ and $p \leq 0.05$, respectively (Table 3.4).

The results of the combined analysis indicated that the number of grains per spike of the tested cultivars under the applied nitrogen rates ranged from 8 to 38 kernels per spike. The highest and lowest numbers of grains per spike were recorded for the *Utuba* cultivar at 184 kg N ha⁻¹ and the *Mangudo* cultivar at 0 kg N ha⁻¹, respectively (Table 3.5). Increasing the nitrogen rate from 0 to 92 kg N ha⁻¹ led to an increase in the number of grains per spike of the *Mangudo* cultivar, whereas increasing the nitrogen rate from 0 to 138 kg N ha⁻¹ increased the number of grains per spike of the *Utuba* cultivar (Table 3.5). Conversely, the number of grains per spike for the *Utuba* cultivar at any nitrogen fertilizer rate was higher compared to that of the *Mangudo* cultivar, which may be due to genetic variability between the tested cultivars in terms of nitrogen use efficiency under the same nitrogen fertilizer application. Furthermore, previous research reports have shown that the number of grains per spike was influenced by the application of nitrogen rates, the cultivars, and their interactions (Kubar *et al.*, 2021; Shoukat *et al.*, 2023).

Grain yield

The combined data analysis over the two years revealed that the main effect of nitrogen fertilizer rates had a significant impact on grain yield at $p \leq 0.01$, while the interaction effect

of cultivar and nitrogen rate significantly affected the grain yield of durum wheat at $p \leq 0.05$. In contrast, the main effect of cultivar did not have a significant impact on grain yield at $p > 0.05$ (Table 3.6).

The combined data results showed that grain yield production under the tested nitrogen rates ranged from 0.65 to 4.8 t ha⁻¹. The highest ton per hectare (t/ha) and lowest grain yields per hectare were obtained from the *Utuba* cultivar at 184 kg N ha⁻¹ and 0 kg N ha⁻¹ of nitrogen fertilizer rates, respectively. As nitrogen fertilizer rates increased from 0 to 184 kg N ha⁻¹, the increased grain yield of *Mangudo* and *Utuba* cultivars mathimatically (Table 3.7). Conversely, in the *Mangudo* cultivar, increasing the nitrogen fertilizer rate from 0 to 92 kg N ha⁻¹ significantly enhanced grain yield, while increasing it from 92 to 184 kg N ha⁻¹ did not significantly increase the grain yield of the *Mangudo* cultivar. However, in the *Utuba* cultivar, increasing nitrogen rates from 0 to 184 kg N ha⁻¹ significantly increased grain yield (Table 3.7). However, application of nitrogen rates from 138 to 184 kg N ha⁻¹ increased grain yield of the *Mangudo* and *Utuba* cultivars but not significantly different (Table 3.7). Yet, the response of *Mangudo* cultivar under the application of 138 kg N ha⁻¹ did not significantly different with the *Utuba* cultivar at the application of 184 kg N ha⁻¹ this result might be due to the response of cultivars to the application of nitrogen rates. On the other word result indicated that the responce of cultivars to nitrogen rate mostly affected by the genetic factor of the tested cultivars.

Therefore, the response of cultivars to nitrogen fertilizer rates significantly affected the grain and straw production of durum wheat. In this regard, previous research has also indicated that increasing nitrogen fertilizer rates significantly increases the grain yield of wheat due to the response of wheat cultivars to nitrogen rate (Boulelouah *et al.*, 2022; Ghimire *et al.*, 2021).

Table 3.6. Mean square results for yield of durum wheat cultivars (combined over 2022 and 2023 cropping years)

Source of variation	Degrees of freedom	Grain yield (t ha ⁻¹)	Biomass yield (t ha ⁻¹)	Straw yield (t ha ⁻¹)	Harvest index (%)
Replication (R)	2	0.03	0.7	0.19	0.00188
Years (Y)	1	14.1*	131.6*	59.92*	0.0369*
Cultivar (C)	1	0.04 ^{ns}	0.1 ^{ns}	0.03 ^{ns}	0.00023 ^{ns}
Nitrogen rates (N)	4	33.5**	144.8**	38.97**	0.008*
Y*C	1	0.4*	0.7*	0.06 ^{ns}	0.00228 ^{ns}
Y*N	4	0.1**	1.8*	1.35*	0.00344*
C*N	4	0.2*	0.4*	0.07**	0.00119*
Y*C*N	4	0.05*	0.2*	0.13*	0.00058*
Error	38	0.2	0.9	0.27	0.00162
Grand mean		3.10	6.77	3.67	45.8
CV (%)		12.74	13.05	14.16	8.87

ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. Y*C= Years and Cultivar interaction, Y*N= Years and Nitrogen interaction, C*N= Cultivar and Nitrogen interaction, Y*C*N= Years, Cultivar, and Nitrogen interaction, CV (%) = Percentage of coefficient of variation.

Biomass yield

The results of the combined data analysis over the years indicated that the main effect of nitrogen rates significantly influenced the biomass yield of durum wheat cultivars at $p \leq 0.01$. Similarly, all interaction effects of the tested factors had a significant impact on the biomass yield of durum wheat at $p \leq 0.05$. Conversely, the main effect of the cultivars did not have a significant effect on the biomass yield of durum wheat at $p > 0.05$ (Table 3.6).

The results of the combined data analysis showed that as the amount of nitrogen rates increased from 0 to 184 kg N ha⁻¹, the biomass yield of the tested cultivars increased (Table 3.7). However, the increase in nitrogen fertilizer rates from 0 to 92 kg ha⁻¹ significantly boosted the biomass yield of both tested durum wheat cultivars. In contrast, increasing the nitrogen rate from 92 to 184 kg ha⁻¹ did not a significant difference in the biomass yield of durum wheat cultivars (Table 3.7). The *Utuba* cultivar recorded the smallest biomass yield per hectare at 0 kg N ha⁻¹, while it achieved the highest biomass yield at 184 kg N ha⁻¹ (Table 3.7). Consistent with the current research findings, previous reports have also confirmed that nitrogen fertilizer rates affect the biomass yield of wheat cultivars (Khan *et al.*, 2022; Zerihun Tufa *et al.*, 2022).

Table 3.7. The mean performances for yield, biomass yield, straw yield, and harvest index of durum wheat cultivars over 2022 and 2023 cropping years at DZARC.

Cultivar	Nitrogen rate (kg ha ⁻¹)	Grain yield (t ha ⁻¹)	Biomass yield (t ha ⁻¹)	Straw yield (t ha ⁻¹)	Harvest index (%)
<i>Mangudo</i>	0	0.8 ^e	1.9 ^d	1.16 ^d	38.9 ^h
<i>Mangudo</i>	46	2 ^d	4.7 ^c	2.69 ^c	42.8 ^g
<i>Mangudo</i>	92	4.1 ^{bc}	8.6 ^b	4.45 ^b	48.3 ^a
<i>Mangudo</i>	138	4.3 ^{ab}	9.2 ^{ab}	4.91 ^{ab}	46.6 ^c
<i>Mangudo</i>	184	4.4 ^{ab}	9.7 ^a	5.25 ^a	45.9 ^d
<i>Utuba</i>	0	0.65 ^e	1.6 ^d	0.89 ^d	44.3 ^e
<i>Utuba</i>	46	1.95 ^d	4.5 ^c	2.55 ^c	43.3 ^f
<i>Utuba</i>	92	3.75 ^c	8.3 ^b	4.52 ^b	45.5 ^d
<i>Utuba</i>	138	4.25 ^b	9.3 ^{ab}	4.90 ^{ab}	47.3 ^b
<i>Utuba</i>	184	4.75 ^a	10.2 ^a	5.37 ^a	47.4 ^b
Grand mean		3.1	6.77	3.67	45.8
LSD 5%		12.74	1.03	0.61	0.47
CV (%)		0.46	13.05	14.16	8.87
LS		**	**	**	*

Mean followed by the same letter are non-significant. LSD (%) = Listed significant different at 5% level, and CV (%) = Percentage of coefficient of variation, LS=level of significant.

Straw yield

The results of the combined data analysis over the two years indicated that the main effect of nitrogen rates and the interaction effect of cultivar with nitrogen rates significantly affected the straw yield of durum wheat at $p \leq 0.01$ and $p \leq 0.05$, respectively. In contrast, the main effect of the cultivars did not have a significant impact on the straw yield of durum wheat at $p \leq 0.05$ (Table 3.6).

The combined data revealed that the straw yield of durum wheat under the tested nitrogen rates ranged from 0.89 to 5.37 t ha⁻¹. The highest straw yield was obtained from the *Utuba* cultivar at a nitrogen rate of 184 kg N ha⁻¹, while the smallest straw yield per hectare was recorded from the *Utuba* cultivar at a nitrogen rate of 0 kg ha⁻¹. Furthermore, increasing the nitrogen fertilizer rates from 0 to 184 kg ha⁻¹ numerically increased the straw yield of the tested cultivars (Table 3.7). Notably, the increase in nitrogen fertilizer rates from 0 to 92 kg ha⁻¹ stastically significantly boosted the straw yield of both cultivars, whereas increasing the nitrogen rate from 138 to 184 kg ha⁻¹ did not a significant increase in the straw yield of the tested cultivars (Table 3.7). Additionally, both cultivars tested under the same nitrogen rates did not show a significant difference in straw yield, indicating that the *Utuba* and *Mangudo* cultivars did not exhibit differing responses in straw production at any nitrogen fertilizer rate. In line with these findings, previous research has confirmed that wheat cultivars have

different response to nitrogen fertilizer use and the production of straw yield in wheat cultivars (Gawdiya *et al.*, 2023; Hlisnikovský *et al.*, 2024).

Harvest index

The combined data analysis over the two years revealed that both the main effect of nitrogen rates and the interaction effect of cultivar and nitrogen rates significantly affected the harvest index of durum wheat at $p \leq 0.05$. In contrast, the main effect of cultivar did not significantly affect the harvest index of durum wheat at $p > 0.05$ (Table 3.6).

The highest (48.3) harvest index of the *Mangudo* cultivar was recorded at the application of 92 kg ha⁻¹ however significant different with the application of other tested nitrogen fertilizer rates. On the other hand, the highest (47.4) harvest index of the *Utuba* cultivar was recorded at the application of 184 kg ha⁻¹ though not significant different with the application of 138 kg N ha⁻¹ (Table 3.7). Increasing nitrogen fertilizer rates from 0 to 92 kg ha⁻¹ significantly enhanced the harvest index of the *Mangudo* cultivar; however, increasing the nitrogen rate from 92 to 184 kg ha⁻¹ decreased the harvest index of this cultivar (Table 3.7). On the other hand, increasing of nitrogen fertilizer rates from 0 to 184 kg ha⁻¹ increased the harvest index of the *Utuba* cultivar (Table 3.7). This result indicates that the grain yield of the tested cultivars significantly increased until the nitrogen rate reached 92 kg N ha⁻¹ for *Mangudo* cultivar. However, increasing the nitrogen rates from 92 to 184 kg N ha⁻¹ did not affect the grain yield of the *Mangudo* cultivar, which in turn did not affect their harvest index. However, increasing the nitrogen rates from 0 to 184 kg N ha⁻¹ did a significant increment of grain yield of the *Utuba* cultivar, which affect their harvest index. The variability of harvest index between the tested cultivars due to the response of cultivar to the application of nitrogen rates. In this regard, the previous research has confirmed that nitrogen fertilizer rates affect the harvest index of wheat cultivars (Zhang *et al.*, 2022; Zhang *et al.*, 2024).

3.3.3. Responses of Durum Wheat Grain Quality to Nitrogen Rates.

3.3.3.1. Grain quality parameters

Thousand kernel weight

The combined data analysis of variance over the two years revealed that the main effects of cultivar ($p \leq 0.01$) and nitrogen fertilizer rates ($p \leq 0.01$), as well as their interaction effect ($p \leq 0.05$), had a significant impact on the thousand kernel weight of durum wheat (Table 3.8).

The combined data analysis over the years showed that the thousand kernel weight increased as nitrogen rates were raised for both tested cultivars. Consequently, the highest thousand kernel weight (g) was recorded for the *Mangudo* cultivar at a rate of 184 kg N ha⁻¹, while the lowest was observed for the *Utuba* cultivar at a rate of 0 kg N ha⁻¹ (Table 3.9). Nevertheless, increasing the nitrogen fertilizer rate from 0 to 46 kg N ha⁻¹ significantly improved the thousand kernel weight (g) of both *Mangudo* and *Utuba* cultivars, whereas increasing nitrogen rates from 46 to 184 kg N ha⁻¹ did not result in a significant increase in the thousand kernel weight for either cultivar. Alternatively, the mean average value of the thousand kernel weight recorded for *Mangudo* increased by 9.48 g compared to the *Utuba* cultivar. This is in accordance with the preceding research findings of Alemayehu *et al.* (2023), which indicated that the thousand kernel weight (g) was primarily influenced by cultivar responses to nitrogen rates. Additionally, Stefanova-Dobrova and Muhova (2024) noted that nitrogen rates and growing climate conditions also affect the thousand kernel weight (g) of wheat.

Table 3.8. Mean square results for kernel weight, hectoliter weight, starch and protein contents of the durum wheat cultivars combined over 2022 and 2023 cropping years

Source of variation	Degrees of freedom	Thousand kernel weight (g)	Hectoliter weight (kg/hl)	Starch content (%)	Protein content (%)
Year (Y)	1	252.2**	29.4*	7.6 ^{ns}	8.06**
Cultivar (C)	1	1372.8**	5.4 ^{ns}	0.9 ^{ns}	76.2**
Nitrogen (N)	4	323.6**	173.1**	9.1*	3.4**
Y*C	1	2.8*	5.4*	6.3*	0.5*
Y*N	4	0.57*	4.8*	1.4*	0.2*
C*N	4	17.07*	4.1*	0.1*	0.03*
Y*C*N	4	0.57*	5.0*	0.4*	0.08*
Error	38	7.40	6.4	2.0	0.3
Grand mean		39.0	44.8	69.64	12.8
CV (%)		6.98	5.65	2.02	4.44

ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. Y*C= Years and Cultivar interaction, Y*N= Years and Nitrogen interaction, C*N= Cultivar and Nitrogen interaction, Y*C*N= Years, Cultivar, and Nitrogen interaction, CV (%) = Percentage of coefficient of variation.

Hectoliter weight

The combined data analysis over the two years showed that the main effect of nitrogen rates significantly impacted the hectoliter weight (kg/hl) of durum wheat at $p \leq 0.01$, while the interaction effect between cultivar and nitrogen rate significantly affected the hectoliter weight (kg/hl) at $p \leq 0.05$. However, the main effect of cultivar did not affect the hectoliter weight of durum wheat at $p > 0.05$ (Table 3.8).

The highest hectoliter weight (kg/hl) was recorded for the *Mangudo* cultivar at 184 kg N ha⁻¹, while the lowest hectoliter weight was obtained for the *Utuba* cultivar at 0 kg N ha⁻¹ (Table 3.9). The average hectoliter weight for the *Mangudo* cultivar increased by 2.6% compared to the mean hectoliter weight (kg/hl) of the *Utuba* cultivar. Furthermore, increasing the rate of nitrogen fertilizer from 0 to 184 kg N ha⁻¹ improved the hectoliter weight (kg/hl) of durum wheat. However, the hectoliter weight recorded at 184 kg N ha⁻¹ was significantly different from the values recorded at 0 to 138 kg N ha⁻¹ (Table 3.9). Thus, the results of this research indicate that the hectoliter weight (kg/hl) of the tested cultivars was affected by all rates of nitrogen fertilizer, with the maximum hectoliter weight observed at 184 kg N ha⁻¹. Additionally, the highest hectoliter weight was recorded for the *Mangudo* cultivar compared to *Utuba* at the same nitrogen rates, which can be attributed to genetic variations. In support of this, the preceding report also indicated that different nitrogen fertilizer application rates affected the hectoliter weight and other yield component parameters of wheat cultivars (Khan *et al.*, 2022).

Starch content

The pooled data analysis revealed that the main effects of nitrogen rates and their interaction with cultivar significantly affected the starch content at $p \leq 0.05$, while the tested cultivars had no significant effect on the starch content of durum wheat at $p > 0.05$ (Table 3.8).

The lowest starch content (%) was recorded for the *Utuba* cultivar at 0 kg N ha⁻¹, which was statistically non-significant from all tested nitrogen rates except for 184 kg N ha⁻¹. Conversely, the highest starch content (%) among the tested cultivars was observed at 184 kg N ha⁻¹, although it was not significantly different from the starch content recorded at 138 kg N ha⁻¹ (Table 3.9). Therefore, based on this researcher result increased the amount of nitrogen rates from 0 to 46 kg N ha⁻¹, the starch content in the grain also increased. However,

increasing the nitrogen rate from 46 to 184 kg N ha⁻¹ had no significant effect on the starch content (%) of durum wheat cultivars. Previous research indicated that the starch content (%) of wheat cultivars significantly increased at critical levels of nitrogen, but nitrogen rates above these critical levels did not affect grain starch content (Xiong *et al.*, 2014; Lv *et al.*, 2021; Li, H *et al.*, 2024).

Table 3.9. The mean performances for kernel weight, hectoliter weight and starch content of durum wheat at Debre Zeit (combined over 2022 and 2023 cropping years)

Cultivar	Nitrogen rate (kg ha ⁻¹)	Thousand kernel weight (g)	Hectoliter weight (kg/hl)	Starch content (%)	Protein content (%)
<i>Mangudo</i>	0	37.5 ^d	40.2 ^{fg}	69 ^{bc}	11 ^f
<i>Mangudo</i>	46	41.5 ^c	42.5 ^e	69.65 ^{a-c}	11.4 ^{ef}
<i>Mangudo</i>	92	45 ^{ab}	45.5 ^d	69.9 ^{a-c}	11.6 ^{ef}
<i>Mangudo</i>	138	46.5 ^a	48 ^{bc}	70.1 ^{ab}	12.2 ^{de}
<i>Mangudo</i>	184	48 ^a	51 ^a	70.4 ^a	12.4 ^d
<i>Utuba</i>	0	26.2 ^f	39 ^g	68.8 ^c	13.1 ^c
<i>Utuba</i>	46	30.9 ^e	42.3 ^{ef}	69.05 ^{bc}	13.7 ^{bc}
<i>Utuba</i>	92	33.4 ^e	45 ^d	69.4 ^{a-c}	14 ^{ab}
<i>Utuba</i>	138	38.7 ^d	46.05 ^{cd}	69.7 ^{a-c}	14.3 ^{ab}
<i>Utuba</i>	184	41.9 ^{bc}	49.1 ^{ab}	69.95 ^{ab}	14.5 ^a
Grand mean		39.0	44.87	69.59	12.8
LSD 5%		3.18	2.31	1.19	0.66
CV (%)		6.98	4.41	1.46	4.44
LS		*	*	*	*

Mean followed by the same letter are non-significant. LSD (%) = Listed significant different at 5% level, and CV (%) = Percentage of coefficient of variation, LS=level of significant

Protein content

The analysis of the combined data over the two years indicated that the protein content was significantly affected by the main effects of cultivar, nitrogen rates, and their interaction at $p \leq 0.01$ (Table 3.8).

The current research finding showed that as nitrogen rates increased from 0 to 184 kg N ha⁻¹, the protein content (%) of the tested cultivars also increased. However, the highest percentage of protein content (%) was recorded for the *Utuba* cultivar at 184 kg N ha⁻¹, while the lowest protein content was observed for the *Mangudo* cultivar at 0 kg N ha⁻¹ (Table 3.8). Therefore, as the nitrogen rate increased, the grain protein content of durum wheat also increased. In this research, the cultivar *Utuba* exhibited a higher protein content (%) compared to the *Mangudo* cultivar due to the varying responses of the cultivars to nitrogen fertilizer rates. In this line the previous research has also indicated that the grain protein content (%) of wheat cultivars

is affected by nitrogen rates due to nitrogen use efficiency variability between the cultivars (Call *et al.*, 2020; Lollato *et al.*, 2021; An *et al.*, 2024).

Gluten contents

The results of the combined data analysis of variance over the two years revealed that both wet and dry gluten contents were significantly influenced by the main effects of the cultivars and nitrogen rates at $p \leq 0.05$ and $p \leq 0.01$, respectively. The interaction effect of nitrogen rate with cultivar also had a significant impact on the wet and dry gluten contents (%) of durum wheat at $p \leq 0.01$ (Table 3.10).

The combined data analysis showed that the highest wet and dry gluten contents (%) were recorded for the cultivar *Utuba* at a nitrogen rate of 184 kg ha⁻¹, while the lowest wet and dry gluten contents (%) were observed for the *Mangudo* cultivar at a nitrogen rate of 0 kg ha⁻¹. The current research findings indicated that the cultivar *Mangudo* exhibited a non-significant increase in wet gluten content as nitrogen rates increased from 46 to 184 kg ha⁻¹. Similarly, there was also a non-significant increase in wet gluten content (%) for the cultivar *Utuba* as nitrogen fertilizer rates increased from 46 to 184 kg ha⁻¹ (Table 3.11). This research demonstrated that both *Mangudo* and *Utuba* cultivars increased their wet gluten content from 0 to 184 kg N ha⁻¹ under the same production system. However, increasing of nitrogen rates from 46 to 184 kg N ha⁻¹ numerically increased wet gluten content (%) of *Mangudo* but statistically non-significant. Similarly, increasing of nitrogen rates from 46 to 184 kg N ha⁻¹ numerically increased wet gluten content (%) of *Utuba* but statistically non-significant. However, the wet gluten content (%) recorded by *Mangudo* and *Utuba* cultivars under the application of nitrogen rates from 46 to 184 kg N ha⁻¹ significantly different. This result indicated that wet gluten content (%) mostly affected by the genetic factor of the tested cultivars than of nitrogen rates (Table 3.11).

On the other hand, the dry gluten content (%) of the *Mangudo* cultivar showed a non-significant increase from 92 to 184 kg ha⁻¹. On the other hand, increase the nitrogen fertilizer rates from 92 to 138 kg ha⁻¹ did not a significant increment of dry gluten content (%) in the *Utuba* cultivar (Table 3.11). This research result indicated that the tested cultivars increased their dry gluten content (%) by the effect of the genetic factor of the cultivars that was compared to the effect of nitrogen rates under the same production system (Table 3.11). When the nitrogen rate was increased from 92 to 184 kg N ha⁻¹, neither the wet nor the dry

gluten contents of the cultivars showed significant increases, which may have been due to the cultivars' responses to nitrogen rates regarding gluten production. In this context, previous findings have indicated that nitrogen rates affect the gluten contents of wheat cultivars only up to an optimum level (Wang *et al.*, 2021; An *et al.*, 2024). Therefore, the results of the current research suggest that the application of 46 kg N ha⁻¹ and 92 kg N ha⁻¹ increased the wet and dry gluten content of durum wheat, respectively.

Table 3.10. Mean squares values for gluten contents, gluten index and SDS-sedimentation of the durum wheat cultivars (combined over 2022 and 2023 cropping years)

Source of variation	Degrees of freedom	Wet gluten content (%)	Dry gluten content (%)	Gluten index (%)	SDS-sedimentation (ml)
Year (Y)	1	60.0*	8.8*	4.8 ^{ns}	12.2*
Cultivar (C)	1	792.1*	212.7*	843.7**	1016.8*
Nitrogen(N)	4	66.5**	19.5**	57.5*	81.7*
Y*C	1	1.1*	0.8*	43.0*	0.42*
Y*N	4	7.1*	1.0*	0.6*	1.9*
C*N	4	14.4**	0.9**	4.0*	18.8*
Y*C*N	4	11.5**	0.5*	2.1*	7.3*
Error	38	8.7	0.6	8.9	10.5
Grand mean		35.3	13.78	78.13	41.45
CV (%)		8.35	5.70	3.82	7.82

ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. Y*C= Years and Cultivar interaction, Y*N= Years and Nitrogen interaction, C*N= Cultivar and Nitrogen interaction, Y*C*N= Years, Cultivar, and Nitrogen interaction, CV (%) = Percentage of coefficient of variation.

Gluten index

The two years combined data analysis of variance revealed that the gluten index (%) of durum wheat cultivars was significantly affected by the main effects of the tested cultivars, nitrogen rates, and their interaction effects at $p \leq 0.01$ and $p \leq 0.05$, respectively (Table 3.10).

The combined data indicated that the highest gluten index was recorded for the *Utuba* cultivar at a nitrogen application rate of 184 kg ha⁻¹, while the lowest gluten index (%) was observed for the *Mangudo* cultivar at a nitrogen rate of 0 kg ha⁻¹ (Table 3.11). Furthermore, the gluten index (%) recorded for the *Utuba* cultivar was higher than that of the *Mangudo* cultivar at similar nitrogen rates (Table 3.11). This result suggests that the *Utuba* cultivar increased the gluten index (%) compared to the *Mangudo* cultivar, possibly due to genetic differences between the cultivars regarding gluten index production under the same nitrogen rate. In this regard, previous findings have stated that both genotype and nitrogen levels affect the gluten index of wheat (Vida *et al.*, 2014; Blandino *et al.*, 2015).

Table 3.11. Mean performances for gluten contents, gluten index and SDS-sedimentation of durum wheat cultivars at DZARC (combined over 2022 and 2023 cropping years)

Cultivar	Nha ⁻¹ (kg)	Wet gluten content (%)	Dry gluten content (%)	Gluten index (%)	SDS-sedimentation (ml)
<i>Mangudo</i>	0	29.5 ^c	10.4 ^g	72 ^f	33.6 ^e
<i>Mangudo</i>	46	30.5 ^{bc}	11.3 ^f	73.4 ^{ef}	36.5 ^{de}
<i>Mangudo</i>	92	31.8 ^{bc}	12.7 ^{de}	74.9 ^{ef}	38.8 ^{cd}
<i>Mangudo</i>	138	33.2 ^b	12.8 ^{de}	75.8 ^{de}	40.6 ^c
<i>Mangudo</i>	184	33.5 ^b	13.6 ^d	75.9 ^{de}	40.7 ^c
<i>Utuba</i>	0	33.0 ^b	12.2 ^{ef}	78.5 ^{cd}	37.0 ^{c-e}
<i>Utuba</i>	46	39.7 ^a	14.6 ^c	79.9 ^{bc}	44.5 ^b
<i>Utuba</i>	92	40.1 ^a	16.1 ^b	82 ^{ab}	46.3 ^{ab}
<i>Utuba</i>	138	40.5 ^a	16.3 ^b	84 ^a	47.8 ^{ab}
<i>Utuba</i>	184	41.2 ^a	17.5 ^a	85 ^a	48.5 ^a
Grand mean		35.3	13.78	78.13	41.45
LSD 5%		3.45	0.92	3.48	3.79
CV (%)		8.35	5.70	3.82	7.82
LS		**	**	*	*

Mean followed by the same letter are non-significant. LSD (%) = Listed significant different at 5% level, and CV (%) = Percentage of coefficient of variation, LS=level of significant.

SDS-sedimentation

The pooled data analysis of variance over the two years showed that the main effects of the tested cultivars, nitrogen rates, and their interaction had a significant effect on the SDS-sedimentation of the durum wheat cultivars tested at $p \leq 0.05$ (Table 3.10).

The combined data indicated that the highest SDS-sedimentation was recorded for the *Mangudo* and *Utuba* cultivars at 184 kg N ha⁻¹, while the smallest SDS-sedimentation was registered at 0 kg N ha⁻¹. Increasing the nitrogen rates from 0 to 184 kg ha⁻¹ statistically improved the SDS-sedimentation values of the tested cultivars. However, the application of 92 kg of nitrogen per hectare did not significantly increase the SDS-sedimentation values compared to the applications of 138 and 184 kg of nitrogen per hectare in both tested cultivars (Table 3.11). Furthermore, the SDS-sedimentation value of the *Utuba* cultivar was higher compared to that of the *Mangudo* cultivar at all nitrogen rates (Table 3.11). This result indicates that the *Utuba* cultivar consistently achieved higher SDS-sedimentation across nitrogen rates compared to *Mangudo*, which may be attributed to genetic differences between the tested cultivars regarding SDS-sedimentation production under specific growing conditions. Therefore, the application of 92 kg N ha⁻¹ was sufficient for the production of SDS-sedimentation in durum wheat in the study area. In this regard, previous research

findings have also indicated that both genotype and nitrogen rate influence the SDS-sedimentation production of wheat (Gao *et al.*, 2017; Valdés *et al.*, 2020).

3.3.4. Effect of Nitrogen Rates on Nitrogen Uptake and Use Efficiency of Durum Wheat Cultivars.

3.3.4.1. Nitrogen use and utilization efficiency

Nitrogen use efficiency

The combined data analysis of variance over the two years indicated that the main effects of cultivar, nitrogen rates, and their interaction significantly affected the nitrogen use efficiency of durum wheat at $p < 0.01$ (Table 3.12).

Nitrogen use efficiency is calculated based on yield performance, specifically on grain yield per unit of nitrogen used. The combined data analysis of the 2022 and 2023 cropping years revealed that there was variation among durum wheat cultivars in terms of nitrogen use efficiency (Table 3.13). Increasing the nitrogen rate from 0 to 46 kg N ha⁻¹ enhanced the nitrogen use efficiency of both *Mangudo* and *Utuba* cultivars. However, applying nitrogen fertilizer above 46 kg N ha⁻¹ for the *Utuba* cultivar and above 92 kg N ha⁻¹ for the *Mangudo* cultivar led to a decrease in nitrogen use efficiency (Table 3.13). In the current research, nitrogen use efficiency varied from 23.9 to 44.6 kg kg⁻¹, as shown in Table 3.14. The highest and lowest nitrogen use efficiencies were recorded for the *Mangudo* cultivar at 92 kg N ha⁻¹ and 184 kg N ha⁻¹, respectively (Table 3.13). Conversely, the nitrogen use efficiency of the *Utuba* cultivar decreased when the nitrogen rate increased from 46 to 184 kg N ha⁻¹. Thus, the nitrogen use efficiency of both tested cultivars declined as nitrogen rates increased from 92 to 184 kg N ha⁻¹, likely due to a lesser increase in grain yield compared to nitrogen supply. In this regard, several previous studies have indicated that the decrease in nitrogen use efficiency with increasing fertilizer rates is due to diminished grain yield in comparison to nitrogen supply in both bread and durum wheat (Boulelouah *et al.*, 2022). Biradar *et al.* (2024) also noted that nitrogen use efficiency was influenced by the genetic factors of the tested wheat cultivars. Similarly, El-Dayem *et al.* (2024) demonstrated that nitrogen use efficiency in wheat is affected by both the rate of nitrogen applied and the genetic characteristics of the tested cultivars.

Table 3.12. Mean squares value result for the dynamics of nitrogen uptake and use efficiency to the durum wheat production (combined over 2022 and 2023 cropping years)

SV	DF	NUE (kg/kg)	AE (kg/kg)	PE (kg/kg)	APE (kg/kg)	ARE (%)	UE (%)
Replication (R)	2	2.85	6.94	0.006	0.65	1.3	0.038
Year (Y)	1	0.02 ^{ns}	73.26*	1717.4*	82.13*	0.013 ^{ns}	1634*
Cultivar (C)	1	6.5**	2.77*	311.9**	33.75**	236.4*	114.4**
Nitrogen(N)	4	3720.2**	2081**	11331**	2634.6**	45330**	9352**
Y*C	1	0.037 ^{ns}	73.26*	282.5*	82.13**	0.015 ^{ns}	364.8*
Y*N	4	0.016 ^{ns}	24.1*	185.5*	7.61**	0.01 ^{ns}	179*
C*N	4	13.4**	8.06*	30.5**	16.16**	98.6*	14.2**
Y*C*N	4	0.04 ^{ns}	24.09**	31.3*	7.61**	0.006*	98.4*
Error	38	2.01	3.87	18.5	3.81	20.24	5.87
Grand mean		28.27	21.62	48.46	22.85	83.49	46.43
CV (%)		5.01	9.10	8.88	8.54	5.39	5.22

*ns, *and ***, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. SV=Source of variation, DF=Degree freedom, NUE=nitrogen use efficiency, AE=Agronomic efficiency, PE=physiological efficiency, APE=Agro-physiological efficiency, ARE=Apparent recovery efficiency, UE=Utilization efficiency, Y*C= Years and Cultivar interaction, Y*N= Years and Nitrogen interaction, C*N= Cultivar and Nitrogen interaction, Y*C*N= Years Cultivar, and Nitrogen interaction, CV (%) = Percentage of coefficient of variation.

Agronomic efficiency

The pooled data analysis of variance over the two years revealed that the main effects of cultivar and nitrogen rates significantly affected the agronomic efficiency of durum wheat at $p \leq 0.05$ and $p \leq 0.01$, respectively. Additionally, the interaction effect of nitrogen rates and cultivars also significantly impacted the agronomic efficiency of durum wheat at $p \leq 0.05$ (Table 3.12).

The combined data analysis over the two years indicated that the agronomic efficiency values recorded from the two durum wheat cultivars ranged from 19.6 to 35.9 kg kg⁻¹. Supplying 92 kg N ha⁻¹ resulted in the maximum agronomic efficiency, while the lowest agronomic efficiency was observed at 184 kg N ha⁻¹ (Table 3.13). Increasing the nitrogen rate from 0 to 92 kg ha⁻¹ enhanced agronomic efficiency, while raising the nitrogen rates from 92 to 184 kg ha⁻¹ decreased the agronomic efficiency of the tested cultivars (Table 3.13).

This study demonstrated that agronomic efficiency increases up to 92 kg N ha⁻¹; beyond this rate, agronomic efficiency declined for both tested cultivars. This decline may be attributed to the minimal increase in grain yield in the fertilized plots per kilogram of nitrogen applied compared to the grain yield in the unfertilized plots. In line with this, previous research has

indicated that at lower nitrogen rates, wheat plants utilized most of the supplied nitrogen for grain yield (Temesgen *et al.*, 2021). Furthermore, Wogene and Agena (2017) reported that the highest agronomic efficiency of nitrogen occurs at lower rates due to reduced nitrogen losses by evaporation, percolation and leeching of the nitrogen fertilizer by sun and rain-fed water.

Physiological efficiency

The combined data analysis of variance over the two years indicated that the physiological efficiency of durum wheat was significantly affected by the main effects of cultivar, nitrogen rate, and their interaction at $p \leq 0.01$ (Table 3.12).

The current research results showed that the physiological efficiency values ranged from 33.3 to 75.5 (Table 3.13). The maximum physiological efficiency was recorded for the *Utuba* cultivar at 92 kg N ha⁻¹, while the lowest value was observed for the *Mangudo* cultivar at 46 kg N ha⁻¹ (Table 3.13). Furthermore, the physiological efficiency increased as the nitrogen rate rose from 0 to 92 kg N ha⁻¹ for both tested cultivars. However, increasing the nitrogen rate above 92 kg N ha⁻¹ led to a decrease in the physiological efficiency of the cultivars (Table 3.13). This decrease may be attributed to the increased nutrient accumulation in the grain and straw of the fertilized plots at nitrogen rates above 92 kg N ha⁻¹, compared to the increment in biological yield. This finding is consistent with the results of Shrestha *et al.* (2018) and Ma *et al.* (2023), who reported that while increasing nitrogen rates can enhance the physiological efficiency of wheat, physiological efficiency also declines when nitrogen rates exceed the recommended levels which mean the optimum nitrogen rate for wheat growth, development and produced hiegher final yield.

Agro-physiological efficiency

The combined data analysis of variance over the two years revealed that the main effects of cultivar, nitrogen rates, and the interaction between cultivar and nitrogen rates significantly affected the agro-physiological efficiency of durum wheat at $p \leq 0.01$ (Table 3.12).

The analysis indicated that the recorded agro-physiological efficiency ranged from 14.7 to 36.5 kg kg⁻¹. The maximum efficiency was observed in the *Mangudo* cultivar at a nitrogen rate of 92 kg ha⁻¹, while the minimum was noted at 46 kg ha⁻¹ (Table 3.13). In this context, increasing the nitrogen rate from 0 to 92 kg ha⁻¹ enhanced the agro-physiological efficiency

of the tested cultivars, whereas raising the nitrogen rates from 92 to 184 kg ha⁻¹ resulted in a decrease in the agro-physiological efficiency of these cultivars (Table 3.13). This study demonstrated that agro-physiological efficiency increases up to 92 kg N ha⁻¹; beyond this rate, it declines for both tested cultivars, likely due to the minimal increase in grain yield from the fertilized plots per kilogram of nitrogen applied compared to the grain yield in the unfertilized plots. Similarly, the agro-physiological efficiency of the *Mangudo* and *Utuba* cultivars at the application of nitrogen rate from 0 to 92 kg N ha⁻¹. Yet, when nitrogen rates exceeded from 92 kg ha⁻¹, the agro-physiological efficiency of the *Utuba* cultivar was greater than that of the *Mangudo* cultivar (Table 3.13) might be due to variability in grain yield production between the cultivars in response to nitrogen fertilizer. In this regard, previous research indicated that the agro-physiological efficiency of wheat is influenced by the genetic variability of the cultivars' responses to nitrogen rates (Fresew, 2019; Biradar *et al.*, 2024).

Apparent recovery efficiency

The combined data analysis of variance over the years indicated that the apparent recovery efficiency of durum wheat was significantly affected by the main effects of nitrogen rate and cultivars at $p < 0.01$ and $p \leq 0.05$, respectively. Additionally, the interaction effect of nitrogen rates and cultivars significantly influenced the apparent recovery efficiency of durum wheat at $p \leq 0.05$ (Table 3.12).

The apparent recovery efficiency recorded in this research ranged from 67.7% to 178.18%. Furthermore, the two cultivars exhibited significant variation in their responses to apparent recovery efficiency. The highest apparent recovery efficiency was obtained with the application of 92 kg N ha⁻¹ for the *Mangudo* cultivar, while the lowest apparent recovery efficiency was recorded with the application of 184 kg N ha⁻¹ for the *Utuba* cultivar (Table 3.13). The *Mangudo* cultivar demonstrated higher recovery efficiency values at all rates of nitrogen fertilizer applied compared to the *Utuba* cultivar. The higher nitrogen recovery by the *Mangudo* cultivar could be attributed to its ability to recover and efficiently utilize N fertilizer.

However, the variability in highest apparent recovery efficiency between the tested cultivars at the 92 kg nitrogen rate was only 1.92% (Table 3.13), which indicates that the tested cultivars had an equal opportunity to utilize N fertilizer efficiently. In contrast, applying

nitrogen rates above 92 kg N ha⁻¹ increased the apparent recovery efficiency of the *Mangudo* cultivar compared to the *Utuba* cultivar. This observation may be due to the higher grain and straw nitrogen content in the *Utuba* cultivar compared to the *Mangudo* cultivar, which could be a result of the genetic variability of the tested cultivars' responses to nitrogen fertilizer rates. In this regard, previous research has also indicated that the apparent recovery efficiency of nitrogen in wheat is affected by the genetic factors of the tested cultivars in response to nitrogen rates (Sieling and Kage, 2021; Temesgen *et al.*, 2021).

Utilization efficiency

The analysis of variance conducted over the two years revealed that the main effects of nitrogen rate, cultivars, and their interactions had a significant impact on utilization efficiency at $p \leq 0.01$ (Table 3.12).

The current research findings indicated that the utilization efficiency of the tested cultivars ranged from 41.77% to 72.85%. The highest utilization efficiency was achieved by the *Utuba* cultivar at an application rate of 92 kg N ha⁻¹, while the lowest utilization efficiency was recorded for the *Mangudo* cultivar at an application rate of 184 kg N ha⁻¹ (Table 3.13). The *Utuba* cultivar consistently demonstrated higher utilization efficiency values across all nitrogen fertilizer application rates compared to the *Mangudo* cultivar. The superior nitrogen utilization efficiency of the *Utuba* cultivar can be attributed to its ability to effectively use nitrogen fertilizer for grain yield production and to minimize nitrogen loss due to leaching and vaporization. Consequently, the variability in utilization efficiency among the tested cultivars at any given nitrogen rate per hectare may stem from the genetic variability of the cultivars in response to nitrogen utilization efficiency. In line with this, previous research has shown that the utilization efficiency of the tested wheat cultivars is influenced by the genetic factors of the cultivars in response to nitrogen rates (Tahir *et al.*, 2020; Ghimire *et al.*, 2021).

Table 3.13. Mean performances for nitrogen uptake and use efficiency of durum wheat cultivars at DZARC (combined over 2022 and 2023 cropping years)

Cultivar	Nitrogen rate (kg ha ⁻¹)	Nitrogen use efficiency (kg kg ⁻¹)	Agronomic efficiency (kg kg ⁻¹)	Physiological efficiency (kg kg ⁻¹)	Agro-physiological efficiency (kg kg ⁻¹)	Apparent recovery efficiency (%)	Utilization efficiency (%)
<i>Mangudo</i>	0 (Control)	0 ^g	0 ^e	-	-	-	-
<i>Mangudo</i>	46	43.5 ^{ab}	26.1 ^{bc}	33.3 ^e	14.7 ^f	178.18 ^a	59.34 ^c
<i>Mangudo</i>	92	44.6 ^a	35.9 ^a	72.85 ^{ab}	36.5 ^a	98.42 ^c	71.69 ^a
<i>Mangudo</i>	138	31.0 ^d	25.4 ^c	63.5 ^c	30.7 ^{cd}	82.6 ^d	52.45 ^e
<i>Mangudo</i>	184	23.9 ^f	19.6 ^d	61.25 ^c	28.6 ^d	68.2 ^e	41.77 ^g
<i>Utuba</i>	0 (Control)	0 ^g	0 ^e	-	-	-	-
<i>Utuba</i>	46	42.4 ^{bc}	27.2 ^b	39.0 ^d	17.2 ^e	164.25 ^b	64.05 ^b
<i>Utuba</i>	92	40.7 ^c	34.3 ^a	75.5 ^a	34.9 ^{ab}	96.5 ^c	72.85 ^a
<i>Utuba</i>	138	30.8 ^d	26.4 ^{bc}	70.15 ^b	32.95 ^{bc}	79.1 ^d	55.42 ^d
<i>Utuba</i>	184	25.8 ^e	22.6 ^d	69.05 ^b	32.9 ^{bc}	67.7 ^e	46.74 ^f
Grand mean		28.27	21.62	48.46	22.85	83.49	46.43
CV (%)		5.01	9.10	8.88	8.54	5.39	5.22
LSD 5%		1.65	2.30	5.03	2.28	5.25	2.83
LS		**	*	**	**	*	**

Mean followed by the same letter are non-significant. LSD (%) = Listed significant different at 5% level, and CV (%) = Percentage of coefficient of variation, LS=level of significant.

3.3.5. Partial Budget

Based on the partial budget analysis of the combined data from the cropping years, the application of a nitrogen fertilizer rate of 92 kg ha⁻¹ resulted in net benefits of 180,700 birr and 170,500 Birr from the *Mangudo* and *Utuba* cultivars, respectively (Table 3.14). The marginal rates of return were 3,371.5% for *Mangudo* and 2,360.0% for *Utuba*, indicating that for each birr invested in the new technology, the producer can recover the one birr invested plus an additional return of 33.7 birr and 23.6 Birr from the production of *Mangudo* and *Utuba* cultivars, respectively (Table 3.14). However, the partial budget analysis indicated that the *Mangudo* cultivar yielded a higher net benefit under the nitrogen treatment of 92 kg N ha⁻¹ compared to the *Utuba* cultivar.

The partial budget analysis indicated that the highest percentage of marginal rate of return was recorded with 92 kg N ha⁻¹ for both tested cultivars. For instance, the marginal rates of return of 3371.5% and 2360.0% (Table 3.14) were recorded from the nitrogen treatment of 92 kg N ha⁻¹ in the *Mangudo* and *Utuba* cultivars, respectively. This implies that for each Birr invested in the cultivation of the tested cultivars, farmers can recover their investment of one Birr plus an additional return of 33.7 Birr and 23.6 Birr from *Mangudo* and *Utuba* production, respectively (Table 3.14).

As a result, the application of a nitrogen fertilizer rate of 92 kg ha⁻¹ yielded net benefits of 180,700 Birr and 170,500 Birr from the *Mangudo* and *Utuba* cultivars, respectively (Table 3.14). Accordingly, the results of the partial budget analysis showed that the *Mangudo* cultivar was the most profitable for local farmers compared to the *Utuba* cultivar under the application of 92 kg N ha⁻¹. Consequently, the difference in profitability between the tested cultivars was attributed to grain and straw production variability due to the genetic variability of the cultivars in response to nitrogen rates under the same nitrogen rate application. Therefore, the *Mangudo* cultivar is recommended for farmers in the study area and in regions with similar agro-ecological conditions.

Table 3.14. Partial budget analysis for nitrogen treatments research at DZARC.

Cultivars	N (kg)	Unadjusted yield (t ha ⁻¹)		Adjusted yield (t ha ⁻¹)		Gross- benefit (birr)	N-cost (birr)	Net- benefit (birr)	MRR (%)
		Grain	Straw	Grain	Straw				
<i>Mangudo</i>	0	0.8	1.16	0.72	1.04	39,200	0	39,200	-
	46	2	2.69	1.8	2.42	66,200	3500	62,700	671.4
	92	4.1	4.45	3.69	4.01	187,700	7000	180,700	3371.5
	138	4.3	4.92	3.87	4.43	199,100	10,500	188,600	225.7
	184	4.4	5.25	3.96	4.73	205,700	14,000	191,700	88.6
<i>Utuba</i>	0	0.65	0.89	0.59	0.80	31,600	0	31,600	-
	46	1.9	2.55	1.71	2.30	91,400	3500	87,900	1608.5
	92	3.8	4.52	3.42	4.07	177,500	7000	170,500	2360.0
	138	4.3	4.91	3.87	4.42	199,000	10,500	188,500	514.3
	184	4.8	5.37	4.32	4.83	221,100	14,000	207,100	531.4

NB: N= Nitrogen, MRR (%) = Marginal rate of return. Percent marginal rate of return (MRR) was calculated as changes in net benefit (raised benefit) divided by changes in cost (raised cost).

3.4. CONCLUSION

It was reported that durum wheat is one of the dominant crops in Ethiopian agriculture. Optimizing the nitrogen fertilizer rate for durum wheat production under specific soil and growing conditions was considered quite important. The current study indicated that increasing nitrogen rates from 0 to 184 kg N ha⁻¹ enhanced all the tested parameters, except for the starch content of the durum wheat cultivars. The highest and lowest values for the tested parameters were recorded at 184 kg N ha⁻¹ and 0 kg N ha⁻¹, respectively. Results of the partial budget analysis indicated that the application of 92 kg N ha⁻¹ registered the highest marginal rate of return for both tested cultivars. However, the marginal rate of return recorded for the *Mangudo* cultivar was higher compared to that of the *Utuba* cultivar. As a result, the cultivation of the *Mangudo* cultivar with an application of 92 kg N ha⁻¹ was found to be more profitable than the other nitrogen treatments. Therefore, the application of 92 kg N ha⁻¹ was recommended as one of the optimal nitrogen fertilizer rates. Moreover, the *Mangudo* cultivar was noted for its high grain yield and straw production in the study area. In conclusion, it was asserted that the cultivation of the *Mangudo* cultivar at 92 kg N ha⁻¹ was advantageous in the study area and in regions with similar agro-climatic conditions.

3.5. REFERENCES

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4. EFFECTS OF NITROGEN FERTILIZER RATES AND IRRIGATION INTERVALS ON YIELD, GRAIN QUALITY AND NITROGEN USE EFFICIENCY OF DURUM WHEAT (*Triticum turgidum* L.) AT DEBRE ZEIT IN CENTRAL ETHIOPIA

ABSTRACT

Wheat production under irrigated system is a recent phenomenon in Ethiopia. However, the recommended nitrogen rates and irrigation intervals for durum wheat production under such systems have not been thoroughly studied. Therefore, this study was conducted to examine the effects of nitrogen rate and irrigation intervals on the growth, yield, grain quality, and nitrogen use efficiency of durum wheat. The experiments were conducted at Debre Zeit Agricultural Research Center during the consecutive cropping years of 2022/23 and 2023/24. The treatments consisted of five nitrogen rates (control, 46 kg ha⁻¹, 92 kg ha⁻¹, 138 kg ha⁻¹, and 184 kg ha⁻¹) and three irrigation intervals (7-day (I₁), 10-day (I₂), and 13-day (I₃) intervals), arranged factorially in a Split Plot Design (SPD) with three replications. The crop was planted on November 16, 2022, and November 15, 2023. The analysis of the results revealed that the main effects of nitrogen rate, irrigation intervals, and their interactions significantly affected the tested parameters. The mean performance data recorded from the interaction of irrigation intervals and nitrogen rate showed maximum population density (469 and 454 plants m⁻²) and plant height (109 cm and 106 cm) at a nitrogen application of 184 kg ha⁻¹ with I₁ (irrigated every seven days) during the 2022/23 and 2023/24 cropping years, respectively. The maximum values of productive tillers per plant (14.5 and 14) and grains per spike (67 and 66), recorded during the 2022/23 and 2023/24 years, were obtained at the interaction of 184 and 138 kg ha⁻¹ at I₁ irrigation frequency, respectively. Similarly, the highest grain yield (7t ha⁻¹ and 6.7t ha⁻¹) and biological yield (17.5 t ha⁻¹ and 15.2 t ha⁻¹) were obtained from the application of 138 kg N ha⁻¹ at I₁ irrigation intervals during the 2022/23 and 2023/24 years, respectively. However, the highest values of protein and gluten content were recorded at the application of 184 kg N ha⁻¹ with I₃ irrigation intervals. The economic analysis also indicated that the net income (Birr 367,520.00), benefit-cost ratio (BCR) of 15.6%, and marginal rate of return (MRR) of 1563.91% were noted from the plots receiving 138 kg ha⁻¹ at every ten-day irrigation interval (I₂). Therefore, applying 138 kg N ha⁻¹ with irrigation every ten days per cropping year will be economically feasible for durum wheat production in the study area and in regions with similar soil and agro-climatic conditions.

Key words: *Biological yield; Grains per spike; Irrigated system; Productive tillers; Quality.*

4.1. INTRODUCTION

Fertilizer and irrigation water management are essential strategies that significantly impact wheat yield and are vital for countering the negative effects of climate change (Abadi, 2019; Woo *et al.*, 2020; Verma *et al.*, 2023). The growth of a plant results from cell division and enlargement, which primarily depends on the availability of nutrients and water (Wach and Skowron, 2022). Frequent application of water to the root zone optimizes soil moisture, creating a better nutritional environment that aids in the growth and development of the plant (Malik *et al.*, 2022). High-yielding agronomic management practices for crop production can be sustained through effective farm-level water management and control systems (Yadav *et al.*, 2022). For instance, to achieve the maximum yield potential, farmers must apply the optimal amount of water during the critical growth stages of their crops (Aydm, 2022).

Irrigation is a crucial agronomic practice to meet the normal demands of wheat production, especially in arid and semi-arid regions (Si *et al.*, 2023). Currently, water resources available for irrigation are very limited, and how to utilize this limited water to achieve the greatest benefit per unit is a significant issue; thus, determining the optimal irrigation level is essential for enhancing wheat yield. Irrigation scheduling is a critical management practice to maintain optimum soil moisture for proper plant growth and production (Beshir, 2017). Jemal Hassen *et al.* (2022) revealed that among the irrigation level treatments (100%, 75%, and 50% ET_c), the highest grain yield of wheat was attained at 100% ET_c. Asmamaw *et al.* (2022) found that wheat production increased with the amount of irrigation water applied.

Nutrients must be supplied to the soil to improve soil fertility and enhance crop productivity (Getinet and Wassie, 2019). Therefore, recommended soil fertility management practices are important for crop production and enhancing productivity (Noulas *et al.*, 2023). This is typically accomplished by using different types of fertilizers, timing applications, and employing various methods of fertilizer application. Earlier research has demonstrated that appropriate fertilizer application increases wheat yield in Ethiopia. For instance, Bekalu and Arega (2016) reported that wheat yield increased by 25.5% due to fertilizer application at fifteen days after planting, using a rate of 23 kg ha⁻¹. Therefore, applying the proper amount of fertilizer is crucial time for achieving a bumper yield of wheat (Yousaf *et al.*, 2014). Conversely, soil moisture concentration directly correlates with fertilizer use efficiency (Dass *et al.*, 2024). Increasing the amount of irrigated water during nitrogen fertilizer application

led to results in significant nitrogen fertilizer loss, which can lead to reduced grain yield of wheat (Li *et al.*, 2022; Khan *et al.*, 2023).

Consequently, managing nitrogen fertilizer is critical for improving production and grain protein content of durum wheat (Zhang *et al.*, 2022). The effect of nitrogen fertilizer rates on wheat production under irrigated production systems is a recent phenomenon investigated by Birke *et al.* (2019), Husen *et al.* (2020), Jemal *et al.* (2022), and Negash *et al.* (2023) in different parts of Ethiopia. However, in the study area, the primary challenges to improving durum wheat yield and grain quality under the irrigated production system are related to the management of nitrogen fertilizer and irrigation schedules for optimal yield and grain quality. As a result, it is essential to generate new technologies regarding nitrogen fertilizer rates and suitable irrigation schedules to enhance the production, productivity, and grain quality of durum wheat. This study aimed to accomplish the following specific objectives:

- i) To determine the effects of nitrogen fertilizer rates and irrigation intervals on nitrogen use efficiency, grain yield, and quality of the *Utuba* durum wheat cultivar.

4.2. MATERIAL AND METHODS

4.2.1. Description of the Study Area

Please refer the description of the study area from subsection 1.11 (Page 32).

4.2.2. Treatments and Experimental Design

The treatments consisted of five nitrogen fertilizer rates (0, 46, 92, 138, and 184 kg N ha⁻¹) and three irrigation intervals (irrigation water applied every 7, 10, and 13 days) that were evaluated at the Debre Zeit Agricultural Research Center in Central Ethiopia over two consecutive cropping seasons in 2022/23 and 2023/24. The tested cultivar, *Utuba*, was selected based on previous research conducted during the irrigated production system in 2020/21 and 2021/22. The *Utuba*, demonstrates high production potential and good grain quality. The experiment was arranged in a split-plot design, with the irrigation intervals serving as the main plot and the nitrogen rate as the subplot, and it was replicated three times. Each main plot measured 23 m in length and 4 m in width (92 m²), while each subplot measured 4 m in length and 3 m in width (12 m²). The spacing between main plots was 3 m, and the spacing between subplots was 2 m. Each subplot contained fifteen rows within each replication, with a spacing of 20 cm between rows.

4.2.3. Experimental Procedures and Management

The experimental land was ploughed using a tractor, and plots were prepared manually. The seeds of the tested durum wheat cultivar *Utuba* was planted by hand drill at a rate of 125 kg per hectare at a depth of 10 cm with the spacing 20cm, after which they were covered with soil. All recommended TSP (Triple Super Phosphate) fertilizer (100 kg ha⁻¹) was applied by banding the granules at the time of planting. Nitrogen fertilizer was applied in two splits at rates of 0, 46, 92, 138, and 184 kg N ha⁻¹, using urea as the nitrogen source. For all fertilizer rates, urea was applied in a split fashion, with 2/3 applied at tiller initiation and 1/3 at the booting stage. The planting dates for the experiments were November 16, 2022/23, and November 15, 2023/24. Three irrigation intervals (7-day (*I*₁), 10-day (*I*₂), and 13-day (*I*₃)) were applied based at 55% water depletion levels (Pereira, 2015). Irrigation water was applied using furrow irrigation, and the irrigation interval was based on hygroscopic soil water tests conducted in the laboratory (Table 4.1). Weeds in the experimental fields were controlled through hand weeding, and there were no issues with diseases or insects during the irrigation experiments. Harvesting was performed manually. The grain quality of the tested

cultivars was evaluated at the Kulumssa Agricultural Research Centre laboratory, and the procedures used during quality analysis are outlined in the data collection section.

Table 4.1. Irrigation intervals and amount during 2022/23 and 2023/24 cropping seasons.

“Seven” days interval (I_1)		“Ten” days interval (I_2)		“Thirteen” days interval (I_3)	
Days after planting	Amount of water (mm)	Days after planting	Amount of water (mm)	Days after planting	Amount of water (mm)
7	9	10	9	13	9
14	11.3	20	17.3	26	25.3
21	15.5	30	28.1	39	28.5
28	20.1	40	43.7	52	35.1
35	33.5	50	53.3	65	134.7
42	34.4	60	149.4	78	133
49	40.7	70	51.4	91	60.9
56	56.4	80	49.9	104	55.7
63	53.9	90	45.8	117	52
70	53.3	100	47.4	130	51.7
77	50.8	110	32.6	Total	585.9
84	49.4	120	38.5		
91	47.6	130	19.5		
98	45.4	Total	585.9		
105	16.3				
112	16.2				
119	16.1				
126	16.0				
Total	585.9				

4.2.4. Data Collection and Measurement

The data collection and measurement for phenology and growth yield related, yield and grain quality parameters please refer on subsection 2.2.5 (Page 45) whereas for nitrogen use and utilization efficiency please refered on section 3.2.4 (Page 93).

4.2.5. Data Analysis

The two years of data analyses were carried out using statistical analysis computer software by Gen-stat software v.19 at split plot design (Gomez and Gomez, 1984). The two years of data mean separation within individual parameters were performed using the least significant difference (LSD) at 5% level of probability.

4.2.6. Partial Budget Analysis

The method of partial budget analysis was please refered section 3.2.6 (Page 94)

4.3. RESULTS AND DISCUSSION

4.3.1. Effects of Nitrogen Rates and Irrigation Intervals on Phenology and Growth Parameters of Durum Wheat.

4.3.1.1. Phenology and growth parameters

Population density per meter square

The results of the analysis of variance demonstrate that both nitrogen application and irrigation intervals, along with their interaction, have a significant impact on the population density of durum wheat per square meter at the specified significance levels ($p \leq 0.05$ for nitrogen and irrigation interaction, and $p \leq 0.01$ for nitrogen alone) (Table 4.2).

The findings from Table 4.3 demonstrate a significant interaction between nitrogen rates and irrigation intervals, affecting population density per square meter across two cropping years. The results show that the population density for the tested cultivar varied widely, with values ranging from 152 to 469 plants per square meter in 2022/23, and from 132 to 454 plants per square meter in 2023/24 cropping year.

Increasing nitrogen rates led to a statistically significant rise in population density per square meter at all irrigation intervals. Notably, the increase in nitrogen from 0 to 138 kg N ha⁻¹ significantly enhanced population density in both years. The most substantial population density was observed with the highest nitrogen application (184 kg N ha⁻¹) at a weekly irrigation interval (I₁), while the lowest density occurred with no nitrogen (0 kg N ha⁻¹) and higher irrigation interval (every thirteen days (I₃)).

Interestingly, the peak population density achieved with 184 kg N ha⁻¹ under I₁ in the 2022/23 cropping year was 3.2% higher than that in 2023/24, indicating some variability between years. Based on this study's results, an application of 138 kg N ha⁻¹, combined with weekly irrigation, emerged as the optimal treatment for maximizing population density across the growing season. This finding aligns with existing literature, including studies by Shirazi *et al.* (2014), which have documented similar trends in wheat population density being significantly influenced by nitrogen levels and irrigation practices.

Table 4.2. Mean squares values of phenology and growth of the durum wheat influenced by nitrogen rates and irrigation intervals in 2022/23 and 2023/24 at DZARC.

Year	Source of variation	DF	Population density per meter square	Days to heading	Days to maturity	Plant height (cm)
2022/23	Replication (R)	2	6047	5.0	45.06	115.27
	Irrigation (I)	2	7866*	9.8 ^{ns}	244.5**	965.4**
	Error (R*I)	4	1577	5.8	20.86	16.57
	Nitrogen (N)	4	111654**	114.2**	183.7*	1547.3**
	I*N	8	481*	0.36*	11.42**	4.40**
	Error (R*I*N)	24	1342	8.32	83.68	119.05
	Grand mean		317.53	59.53	102.93	92.8
	LSD (5%)		67.72	4.95	14.49	16.92
	CV _{R*I*N} (%)		11.54	4.85	8.89	11.76
2023/24	Replication (R)	2	6047	12.82	1.30	44.1
	Irrigation (I)	2	9762*	60.87*	91.40*	537.49**
	Error	4	1577	4.84	20.95	9.06
	Nitrogen (N)	4	111654**	197.73*	221.67*	1533.5**
	I*N	8	481*	3.07*	4.02**	4.6*
	Error (R*I*N)	24	1342	25.91	52.72	68.95
	Grand mean		300.53	56.67	99.53	91.56
	LSD (5%)		61.73	7.97	11.83	12.85
	CV _{R*I*N} (%)		12.19	8.98	7.30	9.07

*ns, *and ***, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. *DF*= Degrees of freedom, *LSD* = List significant different and *CV (%)* = Percentage of coefficient of variation.

Days to heading

The results indicate that in the 2022/23 growing season, the number of days to heading for durum wheat was significantly influenced by the main effect of nitrogen rate ($p \leq 0.01$) and by the interaction effect of nitrogen rate and irrigation interval ($p \leq 0.05$). However, irrigation intervals alone did not have a significant impact on the number of days to heading during that year. In the following year, 2023/24, all three factors nitrogen rate, irrigation interval, and their interaction had a significant effect on the number of days to heading, with significance established at $p \leq 0.05$. This suggests that while nitrogen application is consistently important for the growth cycle of durum wheat, the interaction between nitrogen and irrigation becomes more critical in the second year, likely reflecting changes in environmental conditions or plant responses (Table 4.2).

The results of the mean performance showed that the number of days to heading for durum wheat under the interaction effect of nitrogen rates and irrigation intervals ranged from 54 to 65 days and from 48 to 64 days during the 2022/23 and 2023/24 cropping years, respectively

(Table 4.3). Additionally, the current research indicated that increasing nitrogen rates from 138 to 184 kg N ha⁻¹ resulted in a non-significant increase in the number of days to heading at all irrigation intervals during the 2022/23 cropping year. Similarly, increasing nitrogen rates from 92 to 184 kg N ha⁻¹ also resulted in a non-significant increase in the number of days to heading at all irrigation intervals during the 2023/24 cropping year (Table 4.3). On the other hand, the effect of irrigation treatment did not have a significant impact on the number of days to heading during the 2022/23 cropping year, in contrast to the 2023/24 cropping year. This discrepancy could be attributed to the 12 mm of rainfall recorded during the critical period (flag leaf and spike (head) formation) in 2022/23 compared to the 2023/24 cropping year (Table 2.2).

The highest number of days to heading was recorded with the application of 184 kg of N ha⁻¹ and at 7 days' irrigation interval (I₁), while the smallest was observed with the control nitrogen treatment with thirteen days' irrigation interval (I₃) during both cropping years (Table 4.3). Conversely, the highest number of days to heading recorded under the application of 184 kg of N ha⁻¹ with I₁ during the 2022/23 cropping year increased by 1.5% compared to the highest number recorded in the 2023/24 cropping year under the same conditions. Consequently, increased nitrogen rates with small (low) irrigation interval resulted in an increased number of days to heading, likely due to the effects of the applied nitrogen fertilizer rates and irrigation water intervals. In this regard, various scholars have indicated that the number of days to heading is significantly affected by nitrogen rates and irrigation regimes due to the use of nitrogen fertilizer, the number of days to heading has been prolonged with the help of available soil moisture (Kanwal *et al.*, 2020; Dereje, 2022).

Days to physiological maturity

The analysis of variance revealed that the nitrogen rate at $p \leq 0.05$, and irrigation intervals and their interaction at $p \leq 0.01$ had a significant effect on the number of days to physiological maturity in the 2022/23 cropping season. In contrast, during the 2023/24 cropping year, the effects of nitrogen rate, irrigation intervals, and their interaction were significant at $p \leq 0.05$ (Table 4.2).

The mean performance of days to physiological maturity for crops in the 2022/23 and 2023/24 cropping seasons illustrated variations influenced by nitrogen levels and irrigation practices. Specifically, the duration ranged from 95 to 113 days in 2022/23 and from 90 to

108 days in 2023/24 (Table 4.3). The longest duration to physiological maturity was observed with a nitrogen application of 184 kg N ha⁻¹, accompanied by 7 days' irrigation interval (I₁), while the shortest duration occurred with no nitrogen application and only 13 days' irrigation interval (I₃) in both years. Comparatively, the highest number of days to physiological maturity recorded in 2022/23, with the application of 184 kg N ha⁻¹ and I₁, showed a 4.4% increase over the same conditions in the following year, 2023/24. This variation may be attributed to a recorded rainfall of 12 mm in 2022/23, contrasted with a 0.4 °C increase in maximum temperature during the 2023/24 year (Table 2.2).

The findings indicate that higher nitrogen rates and irrigation intervals are associated with an increased number of days to physiological maturity compared to a control with no nitrogen. This observation aligns with previous studies that demonstrated significant effects of nitrogen rates and irrigation levels on the timing of physiological maturity (Islam *et al.*, 2018; Ararsa, 2023).

Plant height

The results of the statistical analysis indicate that both nitrogen rate and irrigation interval have a substantial impact on plant height, with the effects being statistically significant during both years of the study. In the 2022/23 growing season, the nitrogen rate and irrigation interval, as well as their interaction, were all significant at $p \leq 0.01$, suggesting a strong influence on plant height during that year. In contrast, during the 2023/24 cropping season, while the nitrogen rate and irrigation frequency remained significant at the $p \leq 0.01$, their interaction was significant at $p \leq 0.05$. This indicates a variable response of plant height to the combination of nitrogen and irrigation treatments over the two seasons, although both factors consistently exert influence. Detailed findings, including specific data points and further interpretations, can be found in Table 4.2.

The data regarding plant height in response to nitrogen rate and irrigation interval revealed noteworthy patterns across the two cropping seasons, 2022/23 and 2023/24. The recorded heights ranged from 63 cm to 109 cm in 2022/23 and from 64 cm to 106 cm in 2023/24 (Table 4.3). The interaction of applying 184 kg N ha⁻¹ with the less irrigation interval (I₁) yielded the highest plant height, while the lowest height was observed when no nitrogen (0 kg N ha⁻¹) was applied under the higher irrigation interval (I₃) during both seasons.

Comparative analysis indicated a 1.35% increase in the highest recorded plant height under 2022/23 cropping season compared to the 2023/24 seasons. This variation could be attributed to environmental factors, including 12 mm of rainfall during the 2022/23 year, alongside a 0.4 °C rise in maximum temperature during 2023/24 (Table 1.2). Increased temperatures influence stem elongation rates and, thus, plant height (Kronenberg *et al.*, 2021), while consistent soil moisture levels, facilitated by irrigation interval, further promote plant growth, including height (Shirazi *et al.*, 2014).

The study highlights that the interplay between nitrogen rates and irrigation intervals significantly impacts plant height, with nitrogen applications leading to enhanced growth compared to non-treatment controls. This finding is supported by previous research indicating that both nitrogen levels and irrigation practices substantially influence crop height (Khan *et al.*, 2023; Yang *et al.*, 2024).

Table 4.3. Mean of phenology and growth of the durum wheat influenced by nitrogen rates and irrigation Intervals in 2022/23 and 2023/24 at DZARC.

Treatments		2022/23 cropping year				2023/24 cropping year			
Irrigation intervals (mm)	Nitrogen rates (kg ha ⁻¹)	Population density m ⁻² (No)	Days to heading (No)	Days to maturity (No)	Plant height (cm)	Population density m ⁻² (No)	Days to heading (No)	Days to maturity (No)	Plant height (cm)
I ₁	0	168 ^{gh}	56 ^{gh}	97 ^{bc}	76 ^{e-g}	153 ^{fg}	51.5 ^{de}	94 ^{b-d}	73 ^{ef}
I ₁	46	290 ^{d-f}	58 ^{d-h}	104 ^{a-c}	98 ^{a-d}	275 ^{de}	57 ^{a-d}	97.5 ^{a-d}	96 ^{a-d}
I ₁	92	340 ^{c-e}	61 ^{a-f}	108 ^{a-c}	103 ^{a-c}	325 ^{cd}	58.5 ^{a-d}	103 ^{a-c}	100 ^{a-c}
I ₁	138	423 ^{ab}	62 ^{a-d}	110 ^{ab}	108 ^a	408 ^{ab}	61 ^{ab}	105.5 ^{ab}	105 ^a
I ₁	184	469 ^a	65 ^a	113 ^a	109 ^a	454 ^a	64 ^a	108 ^a	106 ^a
I ₂	0	160 ^h	55 ^{gh}	96 ^{bc}	72 ^{fg}	144 ^{fg}	51 ^{de}	93 ^{cd}	70.7 ^f
I ₂	46	284 ^{ef}	57 ^{e-h}	103.5 ^{a-c}	97 ^{a-d}	268 ^{de}	55.3 ^{b-e}	97 ^{a-d}	95 ^{a-d}
I ₂	92	322 ^{de}	59.5 ^{b-g}	105 ^{a-c}	100 ^{a-c}	306 ^d	57.5 ^{a-d}	102 ^{a-c}	97 ^{a-c}
I ₂	138	400 ^{bc}	61.5 ^{a-e}	106 ^{a-c}	105 ^{ab}	384 ^{bc}	60.3 ^{a-c}	104 ^{a-c}	103 ^{ab}
I ₂	184	443 ^{ab}	64 ^{ab}	109 ^{a-c}	105.3 ^{ab}	427 ^{ab}	62 ^{ab}	105 ^{a-c}	103.7 ^{ab}
I ₃	0	152 ^h	54 ^h	95 ^c	63 ^g	132 ^g	48 ^e	90 ^d	64 ^f
I ₃	46	230 ^{fg}	56.5 ^{f-h}	97.5 ^{bc}	83 ^{d-f}	210 ^{ef}	52 ^{c-e}	96 ^{b-d}	84 ^{de}
I ₃	92	300 ^{de}	59 ^{c-g}	98 ^{bc}	88 ^{c-f}	280 ^d	52.5 ^{c-e}	98 ^{a-d}	89 ^{cd}
I ₃	138	352 ^{cd}	61.5 ^{a-e}	100 ^{a-c}	91 ^{b-e}	332 ^{cd}	59.5 ^{a-c}	99 ^{a-d}	92 ^{b-d}
I ₃	184	430 ^{ab}	63 ^{a-c}	102 ^{a-c}	94 ^{a-d}	410 ^{ab}	60 ^{a-c}	101 ^{a-d}	95 ^{a-d}
Grand mean		317.53	59.53	102.93	92.80	300.53	56.67	99.53	91.56
CV (%)		11.54	4.85	8.89	11.76	12.19	8.98	7.30	9.07
LSD (5%)		67.72	4.95	14.49	16.92	61.73	7.97	11.83	12.85
LS		*	*	**	**	*	*	**	*

ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. Mean followed by the same letter are non-significant. LSD (%) = Listed significant different at 5% level, and CV (%) = Percentage of coefficient of variation, LS=level of significant, I₁= irrigation events per every seven days' interval per cropping year, I₂=irrigation events every ten days' interval per cropping year, I₃=irrigation events every thirteen days' interval per cropping year.

4.3.2. Effects of Nitrogen Rates and Irrigation Interval on Yield and Yield Related Traits of Durum Wheat.

4.3.2.1. Yield and yield related parameters

Number of productive tillers per plant

The analysis of variance performed in this study demonstrated that nitrogen rates, irrigation intervals, and their interaction significantly influenced the number of productive tillers per plant in durum wheat, with a significance level of $p \leq 0.01$ for both the 2022/23 and 2023/24 cropping years as shown in Table 4.4.

The findings revealed that the combined effect of varying nitrogen rates and irrigation frequencies led to a notable difference in productive tillers, with the number recorded ranging from 2 to 14.5 tillers per plant in 2022/23. and 1 to 14 tillers per plant in 2023/24. (Table 4.5). Specifically, the suitable conditions for the maximum number of productive tillers (recorded at the interaction of 184 kg of N ha⁻¹ with the I₁ irrigation interval) highlight the importance of adequate nitrogen and moisture during critical growth periods. Conversely, the minimum tillers were observed with 0 kg N ha⁻¹ at the I₃ irrigation interval across both years.

The analysis indicated that the highest number of productive tillers was consistently attained with 184 kg of N ha⁻¹ under the I₁ irrigation frequency, which outperformed similar conditions in the 2023/24 cropping year. Notably, the number of productive tillers in 2022/23 exceeded those in 2023/24 by 17.4% (Table 4.5), suggesting that environmental factors, particularly weather variability, may have played a role in this difference (Table 2.2). It is worth noting that higher temperatures can reduced the tiller number in wheat varieties (Tiwari *et al.*, 2017), while narrower irrigation intervals have been documented to increased productive tiller counts in rice (Kima *et al.*, 2014).

Overall, the results affirm that enhancing nitrogen application rates, particularly under narrow irrigation intervals, effectively increases the number of productive tillers when compared to controls with no nitrogen treatment. This aligns with previous research by Yousaf *et al.* (2014), also identified that nitrogen rates and narrow irrigation interval had significant impacts of on tiller development in wheat crop.

Table 4.4. Mean squares values of yield related traits of durum wheat influenced by nitrogen rates and irrigation intervals during 2022/23 and 2023/24 at DZARC.

Year	S.V	DF	Productive tiller plant ⁻¹	Spike length (cm)	Spikelet spike ⁻¹	Grain spike ⁻¹
2022/23	Replication (R)	2	0.07	0.1	1.4	5.27
	Irrigation (I)	2	53.6**	17.52**	82.66**	2442.35**
	Error (R*I)	4	0.06	0.07	1.3	5.3
	Nitrogen (N)	4	115.8**	32.27*	159.99**	721.32*
	I*N	8	5.66**	2.0*	3.058**	48.16**
	Error (R*I*N)	24	0.82	1.07	2.83	23.77
	Grand mean		7.63	7.78	16.75	42.93
	LSD (5%)		1.39	1.58	2.77	7.68
CV _{R*I*N} (%)		11.84	13.26	10.05	11.36	
2023/24	Replication (R)	2	3.26	0.86	1.3	12.60
	Irrigation (I)	2	93.35**	16.2**	44.4**	2490.65**
	Error (R*I)	4	3.26	0.9	1.4	12.58
	Nitrogen (N)	4	114.3**	30.78*	92.07**	697.42*
	I*N	8	7.91**	1.44**	2.78**	47.96**
	Error (R*I*N)	24	0.52	0.7	3.73	33.60
	Grand mean		6.50	7.59	15.57	42.13
	LSD (5%)		2.11	1.56	3.13	9.41
CV _(R*I*N) (%)		11.00	11.02	12.41	13.76	

ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. DF= Degrees of freedom, LSD = List significant different and CV (%) = Percentage of coefficient of variation.

Spike length

The findings from the study on the effects of nitrogen rates and irrigation frequency on the spike length of durum wheat highlight several important trends observed during the 2022/23 and 2023/24 cropping seasons. In 2022/23 and 2023/24 cropping seasons, the main effect of nitrogen rate was significant affect spike length of *Utuba* cultivars at $p \leq 0.05$, along with the main effect of irrigation intervals also having a significant effect at $p \leq 0.01$ both cropping seasons. The interaction effect of nitrogen rates and irrigation intervals was also significant at $p \leq 0.05$ undr 2022/23 cropping season but highly singnificant at $p \leq 0.01$ during 2023/24 cropping season (Table 4.4).

The mean spike length recorded as a result of various nitrogen rates and irrigation frequencies ranged from 5 to 11.5 cm in both cropping years (Table 4.5). Importantly, the longest spike length was achieved with an application of 184 kg of nitrogen per hectare at the I₁ irrigation frequency, which was similar to the spike length observed at I₂ irrigation frequency with the same nitrogen rate (Table 4.5). Conversely, the shortest spike length was noted at the null

nitrogen treatments combined with the I₃ irrigation interval during both cropping seasons. In addition, spike length was none significant under the I₃ irrigation regime across nitrogen rates except the the control (Table 4.5).

The analysis suggests that both increased nitrogen rates and the irrigation interval enhance the spike length of durum wheat when compared to the control treatment with no nitrogen. This aligns with previous research indicating that higher irrigation levels (Baloch *et al.*, 2014) and nitrogen applications (Ararsa, 2023; Popal *et al.*, 2024) promote longer spike lengths. Furthermore, other studies (Kouzegaran *et al.*, 2015; Vaziri *et al.*, 2022) corroborate these results by showing the significant effects of nitrogen rates and irrigation levels on spike length in wheat and barley.

In conclusion, the results emphasize the importance of optimizing nitrogen rate and irrigation interval to achieve improved spike lengths and consequently potentially higher yields in durum wheat cultivation. Further studies could expand on these findings to develop optimal management practices tailored for specific conditions.

Table 4.5. Mean of yield related traits of the durum wheat influenced by irrigation intervals and nitrogen rates in 2022/23 and 2023/24 at DZARC.

Treatments		2022/23 cropping year				2023/24 cropping year			
Irrigation intervals	N ha ⁻¹ (kg)	Productive tiller plant ⁻¹	Spike length (cm)	Spikelet spike ⁻¹	Grain spike ⁻¹	Productive tiller plant ⁻¹	Spike length (cm)	Spikelet spike ⁻¹	Grain spike ⁻¹
I ₁	0	4 ^{ij}	5.5 ^{fg}	11.3 ^{hi}	35.5 ^f	2.5 ^{ij}	6 ^{g-i}	11.5 ^{gh}	34.5 ^e
I ₁	46	6 ^{fg}	7 ^{d-f}	16 ^{fg}	46 ^e	5.5 ^{fg}	6.5 ^{f-i}	15 ^{d-f}	45 ^d
I ₁	92	9 ^c	9 ^{bc}	20 ^{b-d}	52 ^{c-e}	8 ^{de}	8.5 ^{c-e}	17 ^{b-e}	51 ^{b-d}
I ₁	138	12 ^b	10 ^{ab}	22 ^{ab}	67 ^a	12 ^{bc}	9.5 ^{bc}	20 ^{ab}	66 ^a
I ₁	184	14.5 ^a	11.5 ^a	23.5 ^a	61 ^{ab}	14 ^a	11.5 ^a	22 ^a	60 ^{ab}
I ₂	0	3 ^{jk}	5.5 ^{fg}	11 ⁱ	33 ^{fg}	2 ^{ij}	5.5 ^{hi}	11 ^{gh}	33 ^e
I ₂	46	5.5 ^{gh}	6.5 ^{d-g}	15.5 ^{fg}	45 ^e	5 ^{gh}	6.3 ^{g-i}	15 ^{d-f}	45 ^d
I ₂	92	8 ^{cd}	8 ^{cd}	19 ^{c-e}	49.5 ^{de}	7.5 ^{ef}	8 ^{c-f}	16.5 ^{c-e}	49.5 ^{cd}
I ₂	138	11 ^b	10 ^{ab}	21 ^{a-c}	58 ^{bc}	10 ^{cd}	9 ^{cd}	18 ^{b-d}	57 ^{a-c}
I ₂	184	14 ^a	11 ^a	21.5 ^{a-c}	55 ^{b-d}	13 ^{ab}	11 ^{ab}	19 ^{a-c}	54 ^{b-d}
I ₃	0	2 ^k	5 ^g	10 ⁱ	21 ^h	1 ^j	5 ⁱ	10 ^h	20 ^f
I ₃	46	4.5 ^{hi}	6 ^{e-g}	11.5 ^{hi}	27 ^{gh}	3 ^{hi}	5.3 ⁱ	13 ^{f-h}	26 ^{ef}
I ₃	92	6.5 ^{e-g}	7 ^{d-f}	14 ^{gh}	29 ^{f-h}	4 ^{g-i}	7 ^{e-h}	14 ^{e-g}	28 ^{ef}
I ₃	138	7 ^{d-f}	7.3 ^{de}	17 ^{ef}	33 ^{fg}	5 ^{gh}	7.3 ^{e-g}	15.5 ^{d-f}	32 ^e
I ₃	184	7.5 ^{de}	7.5 ^{c-e}	18 ^{d-f}	32 ^{fg}	5.5 ^{fg}	7.5 ^{d-g}	16 ^{c-f}	31 ^e
Grand mean		7.63	7.79	16.75	42.93	6.50	7.59	15.56	42.13
CV _(R*I*N) (%)		11.84	13.26	10.05	11.36	11.0	11.02	12.41	13.76
LSD (5%)		1.39	1.57	2.77	7.68	2.11	1.56	3.13	9.40
LS		**	*	**	**	**	**	**	**

ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. Mean followed by the same letter are non-significant. LSD (%) = Listed significant different at 5% level, and CV (%) = Percentage of coefficient of variation, LS=level of significant, I₁= irrigation events per every seven days' interval per cropping year, I₂=irrigation events every ten days' interval per cropping year, I₃=irrigation events every thirteen days' interval per cropping year, N=Nitrogen fertilizer.

Number of spikelet per spike

The study by Kanwal *et al.* (2020) highlights the crucial role of spikelets per spike in determining the final yield of grain and straw in wheat crops. The current research findings indicate a significant impact of nitrogen rates, irrigation frequency, and their interaction on the number of spikelets per spike in durum wheat across two consecutive cropping years (2022/23 and 2023/24), with a significance level of $p \leq 0.01$ (Table 4.4).

The interaction effects of nitrogen and irrigation indicate a wide range in the mean number of spikelets per spike from 10 to 23.5 in 2022/23 and 10 to 22 in 2023/24 (Table 4.5). Notably, the highest number of spikelets was observed with an application of 184 kg of nitrogen per hectare at the I₁ irrigation frequency. This outcome was statistically similar to that of 138 kg of nitrogen per hectare under the I₃ irrigation frequency, and also comparable at both 138 kg and 184 kg of nitrogen at the I₂ irrigation frequency (Table 4.5). The study further reveals that number of spikelets per spike were none significant difference between I₁ and I₂ irrigation intervals under the application of the same nitrogen rate. On the other hand, I₁ and I₂ irrigation intervals did not significant difference in number of spikelets per spike which was observed under I₃ irrigation interval at control treatment (Table 4.5).

On the other end of the spectrum, the lowest number of spikelets per spike was recorded at the null nitrogen treatment with I₃ irrigation interval during both growing seasons (Table 4.5). This supports the findings that increasing nitrogen rates from 0 to 138 kg per hectare consistently enhanced the spikelet count across all irrigation intervals. The study's results align with previous research indicating that higher nitrogen rates and better irrigation management improve the number of spikelets per spike (Kumar *et al.*, 2024; Mirzakhani and Dadian, 2024). Furthermore, similar conclusions were reached in other studies, affirming that the number of spikelets is significantly influenced by both nitrogen application and irrigation interval (Khan *et al.*, 2023). In summary, recommended nitrogen rates and irrigation intervals is crucial to maximizing the spikelet count, which in turn is likely to enhance durum wheat yields.

Number of grain per spike

The statistical analysis of data revealed that the number of grain per spike of wheat significantly affected by the main effect of nitrogen rate, irrigation intervals and their

interaction at $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.01$ both in 2022/23 and 2023/24 cropping seasons, respectively (Table 4.4).

The analysis of the data indicates that the application of 138 kg of nitrogen (N) per hectare (ha) at the I₁ irrigation interval resulted in the highest number of grains per spike in durum wheat. Notably, the grain count at this nitrogen rate was statistically similar to that observed with 184 kg of N ha⁻¹ at the same irrigation intervals. Additionally, the grain count from the 138 kg N ha⁻¹ treatment was comparable to the counts from both 134 kg and 184 kg N ha⁻¹ at the I₂ irrigation interval, suggesting a level of consistency across all nitrogen applications and irrigation intervals (Table 4.5).

The results underscore that increasing the nitrogen application from 0 to 138 kg ha⁻¹ promotes the number of grains per spike, with 138 kg ha⁻¹ identified as the recommendable rate for enhancing grain production in terms of grains per spike yield. Furthermore, it was observed that higher nitrogen rates, coupled with increased irrigation frequencies, contributed to greater grain counts per spike compared to control treatments that involved no nitrogen fertilization.

Comparative studies in the literature support these findings, demonstrating that grain per spike of wheat tends to increase with elevated irrigation levels (Islam *et al.*, 2018) and that nitrogen rates have a significant positive impact on grain production (Rodríguez-Félix *et al.*, 2014; Li *et al.*, 2022). This reinforces the conclusion that appropriate management of nitrogen and water resources is critical for optimal durum wheat yield.

Grain yield

The statistical analysis of variance indicated that the grain yield of *Utuba* was significantly affected by the main effects of nitrogen rate, irrigation interval, and their interaction at $p \leq 0.01$ in both the 2022/23 and 2023/24 cropping years (Table 4.6).

The results of this study demonstrate a significant interaction between nitrogen rates and irrigation intervals in determining the grain yield of durum wheat across the two cropping seasons (2022/23 and 2023/24). The mean grain yield ranged from 0.3 to 7 t ha⁻¹ in 2022/23 and from 0.4 to 6.7 t ha⁻¹ in 2023/24 (Table 4.7). Notably, the application of 138 kg N ha⁻¹ under the application of I₁ irrigation interval produced the highest grain yield which was compared to all other treatments but none significant difference found in the application of

184 kg N ha⁻¹ under the application I₁ irrigation interval, 138 kg N ha⁻¹ under the application I₂ irrigation interval and 184 kg N ha⁻¹ under the application I₂ irrigation interval, respectively during the 2022/23 cropping season (Table 4.7). In the subsequent season (2023/24), the highest grain yield recorded from 138 kg N ha⁻¹ at the application of I₁ irrigation interval but none significant with the application of 184 kg N ha⁻¹ at the I₁ irrigation interval. However, different trends emerged, as the grain yield from 184 kg N ha⁻¹ at I₁ was not significantly different from the yields recorded from 138 and 184 kg N ha⁻¹ at the I₂ irrigation interval during 2023/24 cropping season.

The data suggest that the application of nitrogen at a rate of 138 kg ha⁻¹ is recommendable rate for higher grain yield across both irrigation intervals, given that yields increased from 0 to 138 kg N ha⁻¹ but decreased from 138 to 184 kg N ha⁻¹ in both cropping seasons. This underscores the prominent influence of nitrogen rates on durum wheat grain yield, more so than irrigation interval. Moreover, the I₁ irrigation interval was superior for grain yield production compared to I₂ and I₃ intervals under the corresponding nitrogen rates. However, the grain yield recorded from I₁ irrigation interval was none significant with I₂ irrigation interval under the same nitrogen rates except 92 kg N ha⁻¹ and 138 kg N ha⁻¹ during 2022/23 and 2023/24 cropping seasons, respectively (Table 4.7). The slight decline in mean yield between the two cropping seasons specifically a 2.13% decreased from 2022/23 to 2023/24 may be attributable to variations in weather conditions experienced during the two seasons. Supporting literature confirms the significant impact that nitrogen fertilizer rates have on wheat grain yield under irrigated conditions, as noted by various studies (Amirhajloo *et al.*, 2023; Huang *et al.*, 2023; Negash Bedaso *et al.*, 2023; Liu *et al.*, 2024).

The cost benefit analysis indicated that I₂ is a superior which was compared to I₁ and I₃ irrigation application (Table 4.16) and as a conclusion, this research underscores the critical role of nitrogen management in enhancing durum wheat yields, suggesting that optimized nitrogen application (138 kg N ha⁻¹) coupled with I₂ irrigation interval can effectively improve grain production in varied climatic conditions.

Table 4.6. Mean squares values of yield of the durum wheat influenced by nitrogen rates and irrigation intervals under 2022/23 and 2023/24 cropping seasons

Year	S.V	DF	Grain yield (t ha ⁻¹)	Biomass yield (t ha ⁻¹)	Straw yield (t ha ⁻¹)	Harvest index (%)
2022/23	Replication (R)	2	0.1	0.78	0.32	0.43
	Irrigation (I)	2	53.0**	174.54**	41.64*	1384.76**
	Error _(R*I)	4	0.16	1.18	0.47	1.06
	Nitrogen (N)	4	32.1**	197.50**	80.29**	2.6 ^{ns}
	I*N	8	3.99**	13.84**	4.3**	5.28*
	Error _(R*I*N)	24	0.17	1.13	0.4	3.12
	Grand mean		3.35	8.67	5.32	38.6
	LSD (5%)		0.74	2.22	1.18	2.85
CV _(R*I*N) (%)		12.46	12.29	11.96	4.85	
2023/24	Replication (R)	2	0.06	0.32	0.10	0.28
	Irrigation (I)	2	26.4**	129.18**	39.06**	27.19**
	Error _(R*I)	4	0.06	0.31	0.11	0.26
	Nitrogen(N)	4	37.3**	188.55**	58.1**	1.04 ^{ns}
	I*N	8	2.34**	11.38**	3.4**	0.46*
	Error _(R*I*N)	24	0.15	0.81	0.26	4.85
	Grand mean		3.28	7.41	4.13	44.26
	LSD (5%)		0.63	1.46	0.83	3.35
CV _(R*I*N) (%)		11.88	12.11	12.29	5.00	

*ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. DF= Degrees of freedom, LSD = List significant different and CV (%) = Percentage of coefficient of variation.*

Biomass yield

The analysis of variance revealed significant effects of nitrogen rates, irrigation intervals, and their interaction on the biomass yield of durum wheat, with a significance level of $p \leq 0.01$ for both the 2022/23 and 2023/24 cropping years (Table 4.6).

The mean performance data indicated that the biomass yield, influenced by the interaction of nitrogen rates and irrigation intervals, ranged from 1.2 t ha⁻¹ to 17.5 t ha⁻¹ in the 2022/23 year and from 0.95 t ha⁻¹ to 15.2 t ha⁻¹ in the 2023/24 year (Table 4.7). The highest biomass yield was achieved with an application of 138 kg of nitrogen per hectare at the I₁ irrigation interval and it followed by biomass yield recorded from 184 kg N ha⁻¹ at I₁ irrigation interval, 138 kg N ha⁻¹ at I₂ irrigation interval, 184 kg N ha⁻¹ at I₂ irrigation interval and at I₁ irrigation interval, 92 kg N ha⁻¹ while the lowest yield occurred with no nitrogen applied at the I₃ irrigation interval throughout both cropping seasons (Table 4.7). This research demonstrated that the highest biomass yield, obtained from the application of 138 kg of N ha⁻¹ at I₁, was superior to the biomass yields from other assessed nitrogen rates at individual irrigation

interval. However, the biomass yield obtained from 138 kg of N ha⁻¹ at I₁ was not significantly different from that of 184 kg of N ha⁻¹ at I₁ irrigation interval in both cropping seasons but significantly different from all nitrogen rates both under I₂ and I₃ irrigation intervals (Table 4.7).

Notably, increasing nitrogen rates from 0 to 138 kg ha⁻¹ resulted in a significant boost in durum wheat biomass yield across all irrigation frequencies in both cropping years, while further increasing nitrogen rates from 138 to 184 kg ha⁻¹ did not lead to significant yield improvements at any irrigation frequency during the same periods (Table 4.7). Consequently, the research concluded that the recommended nitrogen rate for maximizing biomass production of durum wheat in an irrigated system is 138 kg ha⁻¹. This finding aligns with previous studies suggesting that nitrogen rates and irrigation levels significantly impact wheat biomass yield (Pradhan *et al.*, 2013; Si *et al.*, 2020; Jemal *et al.*, 2022).

Table 4.7. Mean of yield of the durum wheat influenced by nitrogen rates and irrigation intervals in 2022/23 and 2023/24 cropping years at DZARC.

Treatments			2022/23 cropping year				2023/24 cropping year			
Irrigation intervals	N (kg)	ha ⁻¹	Grain yield (t ha ⁻¹)	Biomass yield (t ha ⁻¹)	Straw yield (t ha ⁻¹)	Harvest index (%)	Grain yield (t ha ⁻¹)	Biomass yield (t ha ⁻¹)	Straw yield (t ha ⁻¹)	Harvest index (%)
I ₁	0		1.5 ^{e-g}	3.44 ^{gh}	1.94 ^{fg}	43.6 ^a	0.9 ^{h-j}	2.07 ^{i-k}	1.17 ^{hi}	43.4 ^{a-c}
I ₁	46		2.4 ^d	6 ^{ef}	3.6 ^e	40.0 ^b	2.1 ^{fg}	4.83 ^{fg}	2.73 ^{ef}	43.5 ^{a-c}
I ₁	92		5.7 ^b	14.1 ^c	8.4 ^b	40.43 ^b	5.4 ^{cd}	12.42 ^c	7.02 ^b	43.5 ^{a-c}
I ₁	138		7 ^a	17.5 ^a	10.5 ^a	40.0 ^b	6.7 ^a	15.2 ^a	8.5 ^a	44.1 ^{a-c}
I ₁	184		6.8 ^a	17 ^{ab}	10.2 ^a	40.0 ^b	6.3 ^{ab}	14.4 ^{ab}	8.1 ^a	43.76 ^{a-c}
I ₂	0		1 ^{gh}	2.3 ^{hi}	1.3 ^g	43.5 ^a	0.7 ^{ij}	1.54 ^{jk}	0.84 ^{hi}	45.3 ^{a-c}
I ₂	46		2.1 ^{de}	5.1 ^{fg}	3 ^{ef}	41.2 ^{ab}	1.8 ^g	3.96 ^{gh}	2.16 ^{fg}	45.5 ^{ab}
I ₂	92		4.8 ^c	11 ^d	6.2 ^c	43.64 ^a	4.8 ^d	10.5 ^d	5.7 ^c	45.7 ^{ab}
I ₂	138		6.6 ^a	15.2 ^{bc}	8.6 ^b	43.42 ^a	6 ^{bc}	13.1 ^{bc}	7.1 ^b	45.8 ^a
I ₂	184		6.4 ^{ab}	14.7 ^c	8.3 ^b	43.54 ^a	5.7 ^{bc}	12.54 ^c	6.84 ^b	45.4 ^{a-c}
I ₃	0		0.3 ^h	1.2 ⁱ	0.9 ^g	25.0 ^c	0.4 ^j	0.95 ^k	0.55 ⁱ	42.1 ^c
I ₃	46		1 ^{gh}	3.7 ^{gh}	2.7 ^{ef}	27.03 ^c	1.1 ^{hi}	2.51 ^{h-j}	1.41 ^{gh}	43.8 ^{a-c}
I ₃	92		1.2 ^{fg}	4.8 ^{fg}	3.6 ^e	25.0 ^c	1.5 ^{gh}	3.5 ^{g-i}	2 ^{fg}	42.9 ^{a-c}
I ₃	138		1.9 ^{d-f}	7.6 ^e	5.7 ^{cd}	25.0 ^c	3.4 ^e	7.8 ^e	4.4 ^d	43.6 ^{a-c}
I ₃	184		1.6 ^{e-g}	6.4 ^{ef}	4.8 ^d	25.0 ^c	2.5 ^f	5.9 ^f	3.4 ^e	42.4 ^{bc}
Grand mean			3.35	8.67	5.32	38.6	3.28	7.41	4.13	44.26
CV (%)			12.46	12.29	11.96	4.85	11.88	12.11	12.29	5.00
LSD (R*I*N) (5%)			0.74	2.23	1.18	2.85	0.63	1.46	0.83	3.35
LS			**	**	**	*	**	**	**	*

ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. Mean followed by the same letter are non-significant. LSD (%) = Listed significant different at 5% level, and CV (%) = Percentage of coefficient of variation, LS=level of significant, I₁= irrigation events per every seven days' interval per cropping year, I₂=irrigation events every ten days' interval per cropping year, I₃=irrigation events every thirteen days' interval per cropping year, N=Nitrogen fertilizer.

Straw yield

The mean square analysis of variance indicated that the main effect of nitrogen rate ($P \leq 0.05$), irrigation intervals ($P \leq 0.01$) and their interaction ($P \leq 0.01$) significantly affect the straw yield in 2022/23. During 2023/24 cropping season the main effect of nitrogen rate, irrigation intervals and their interaction significantly affected the straw yield of durum wheat at $p \leq 0.01$ (Table 4.6).

The mean performance of the result indicated that the interaction effect of nitrogen rates and irrigation intervals affected the straw yield of durum wheat and ranged from 0.9 to 10.5 t ha⁻¹ and 0.55 to 8.5 t ha⁻¹ during 2022/23 and 2023/24 cropping years, respectively (Table 4.7). The highest straw yield per hectare was recorded at the applied of 138 kg of N ha⁻¹ at I₁ irrigation interval. It was non-significant different with 184 kg of N ha⁻¹ at I₁ irrigation interval but significant different with all nitrogen treatment at any irrigation intervals (Table 4.7) during 2022/23 and 2023/24 cropping seasons. This research result indicated that the straw yield per hectare was variable between the tested years and the straw yield that was recorded from 2022/23 cropping year had increased by 28.8% compared to the straw yield that registered during 2023/24 (Table 4.7). It might be due to the variability of weather condition. For instance, during 2023/24 cropping year 0.4 °C maximum temperatures was increased and it led to facilitating high straw production during 2022/23 (Table 1.2).

In addition of this, increasing of nitrogen rates from 0 to 138 kg ha⁻¹ significantly increased the straw yield of durum wheat whereas increased the nitrogen rates from 138 to 184 kg ha⁻¹ decreased the straw yield at at I₁ and I₂ irrigation intervals both cropping seasons (Table 4.7). However, increasing of nitrogen rates from 46 to 184 kg ha⁻¹ none significant different in straw yield during 2022/23 cropping seasons while increasing of nitrogen rates from 0 to 92 kg ha⁻¹ none significant different in straw yield but increasing of nitrogen rates from 138 to 184 kg ha⁻¹ significantly increased the straw yield during 2022/23 cropping season (Table 4.7). Accordingly, the application of 138 kg ha⁻¹ was the optimum nitrogen rate for straw production of durum wheat under irrigated production system. Regarding this, the preceding research result also indicated that the straw yield of wheat is affected by nitrogen rates and irrigation regimes (Wang *et al.*, 2012; Shirazi *et al.*, 2014).

Harvest index

The analysis of variance revealed that the main effect of irrigation intervals and the interaction between nitrogen rate and irrigation intervals significantly affected the harvest index of durum wheat at the $p \leq 0.01$ and $p \leq 0.05$ levels of significance, respectively, in both tested years. However, the main effect of nitrogen rate did not significantly affect the harvest index of durum wheat at $p > 0.05$ in either year (Table 4.6).

During the 2022/23 cropping year, the highest harvest index recorded with an application of 92 kg of N ha⁻¹ at the I₂ irrigation interval and it not significant different with 0 kg of N ha⁻¹ at the I₁ irrigation interval, and all nitrogen rates under I₂ irrigation interval but significant different with other tested treatments (Table 4.7). However, the highest harvest index next to application of 92 kg of N ha⁻¹ at the I₂ irrigation interval (43.64) have been recorded from the none nitrogen application under I₁ irrigation interval (43.6) (Table 4.7). It might be because of the lower straw yield production (29.3%) compared to grain yield than the other treatments (>30%) (Table 4.7). It leads to increase the harvest index of durum wheat. However, in 2023/24 cropping season, the highest harvest index recorded at the application of 138 kg of N ha⁻¹ at the I₂ irrigation interval and it not significant different with all tested treatments except 0 kg of N ha⁻¹ at the I₃ irrigation interval.

The overall research result indicated that the highest harvest index recorded during 2023/24 cropping season and increased by 14.66% compared to 2022/23 cropping season (Table 4.7). this might be due to the higher straw yield production which increased by 28.8% during 2022/23 cropping season compared to straw yield in 2023/24 cropping season (Table 4.7). It leads to higher harvest index recorded during 2023/24 cropping season. On the other hand, the highest harvest index was observed at the I₂ irrigation interval, followed by I₁ and I₃ intervals, respectively (Table 4.7). Therefore, nitrogen application under narrow irrigation intervals leads to an increase in the harvest index of durum wheat due to an increase in grain yield compared to straw production, resulting in a higher harvest index value. In this regard, previous research indicates that the harvest index of wheat is primarily affected by the interaction of nitrogen fertilizer rate and irrigation levels (Kumar *et al.*, 2018; Singh *et al.*, 2018).

4.3.3. Grain Quality Parameters of Durum Wheat as Affected by Nitrogen Rates and Irrigation Intervals.

4.3.3.1. Grain quality parameters

Thousand kernel weight

In wheat, thousand kernel weight is an important parameter that significantly contributes to grain yield. The trait of thousand kernel weight is crucial for estimating yield compared to other traits. Heavier seeds contribute more to yield, allowing for a more accurate estimation of a line's yield potential based on thousand kernel weight. The statistical analysis of the data presented in Table 4.8 revealed that the main effects of nitrogen rate ($p < 0.05$), irrigation interval ($p < 0.01$), and their interaction ($p < 0.05$) had a significant impact on the thousand kernel weights of wheat.

The results of the study indicated that the interaction between nitrogen rates and irrigation interval significantly affected the thousand kernel weights of durum wheat, which ranged from 25 to 52 g in the 2022/23 growing season and from 23.5 to 51 g in the 2023/24 growing season (Table 4.9). The highest thousand kernel weight was recorded at the interaction of 138 kg N ha⁻¹ with I₁ irrigation interval, followed by 138 kg N ha⁻¹ at I₂ irrigation interval, 184 kg N ha⁻¹ at I₁ irrigation interval, and 184 kg N ha⁻¹ at I₂ irrigation interval, respectively. Conversely, the lowest thousand kernel weight was recorded at the interaction of 0 kg N ha⁻¹ with I₃ irrigation interval during the 2022/23 growing season (Table 4.9). Similarly, during the 2023/24 growing season, the highest thousand kernel weight was again recorded at the interaction of 138 kg N ha⁻¹ with I₁ irrigation interval, followed by 184 kg N ha⁻¹ at I₁ irrigation interval, 138 kg N ha⁻¹, and 184 kg N ha⁻¹ both at I₂ irrigation interval, while the lowest thousand kernel weight was recorded at the interaction of 0 kg N ha⁻¹ with I₃ irrigation interval (Table 4.9).

Moreover, increasing the nitrogen rate from 0 to 184 kg ha⁻¹ correspondingly raised the thousand kernel weights of durum wheat at any irrigation frequency; however, the maximum thousand kernel weight was observed under the narrow irrigation interval (I₁) due to the sufficient soil moisture content during the critical growth period. Additionally, the thousand kernel weight recorded in the 2022/23 growing season increased by 2.94% compared to that registered during the 2023/24 growing season, which may be attributed to weather variability between the two years. For instance, during the 2022/23 growing season, an additional 12

mm of rainfall was recorded, while maximum temperatures increased by 0.4 °C in the 2023/24 growing season (Table 1.2). In this regard, low water stress and higher temperatures affect the thousand kernel weights of wheat varieties (Marcela *et al.*, 2015). Furthermore, prior research has indicated that thousand kernel weights of crops are significantly influenced by the interaction of nitrogen rates and irrigation regimes (Al-Menaie *et al.*, 2021; Ra *et al.*, 2023).

Table 4.8. Mean squares values of grain quality of durum wheat affected by nitrogen rates and irrigation intervals during 2022/23 and 2023/24 cropping years at DZARC

Year	Source of variation	DF	Thousand kernel weight (g)	Hectoliter weight (kg/hl)	Starch content (%)	Protein content (%)
2022/23	Irrigation (I)	2	230.3**	2637.6**	23.76*	28.0**
	Nitrogen (N)	4	802.8*	1193.3**	3.42 ^{ns}	7.1**
	I*N	8	10.0*	85.9**	0.31*	0.05**
	Error	24	16.1	11.2	5.34	0.9
	Grand mean		40.99	58.2	69.29	13.6
	LSD (5%)		6.70	5.5	3.85	1.63
	CV (%)		9.80	5.77	3.34	7.19
2023/24	Irrigation (I)	2	264.5**	2857.9**	42.45*	39.3**
	Nitrogen (N)	4	802.8*	1188.6**	6.19 ^{ns}	7.3**
	I*N	8	10.3*	87.1**	0.2*	0.04**
	Error	24	11.9	11.3	5.98	0.7
	Grand mean		39.82	56.88	68.94	13.86
	LSD (5%)		5.76	5.6	4.08	1.44
	CV(%)		8.68	5.90	3.55	6.23

ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. DF= Degrees of freedom, LSD = List significant different and CV (%) = Percentage of coefficient of variation.

Hectoliter weight

The mean square values from the research revealed that the main effects of nitrogen rates, irrigation interval, and their interaction significantly affected the hectoliter weight of wheat at $p \leq 0.01$ in both production seasons (Table 4.8).

The range of hectoliter weight recorded in this study was from 35 to 81 kg/hl in the 2022/23 cropping season and from 33.1 to 80 kg/hl in the 2023/24 cropping year, respectively (Table 4.9). The highest hectoliter weight was recorded at the interaction of 184 kg of N ha⁻¹ with I₁ irrigation interval, followed by 138 kg of N ha⁻¹ at I₁ irrigation interval, 184 kg of N ha⁻¹ at I₂ irrigation interval, and 138 kg of N ha⁻¹ at I₂ irrigation interval. Conversely, the smallest

hectoliter weight was recorded at the interaction of 0 kg N ha⁻¹ with I₃ irrigation interval in both cropping years (Table 4.9).

The results of the current research showed that the application of nitrogen rates increased from 0 to 184 kg ha⁻¹, leading to an increase in the hectoliter weight of durum wheat regardless of the irrigation interval. However, the highest hectoliter weight observed at 184 kg of N ha⁻¹ with I₁ irrigation interval during both tested years may be attributed to the sufficient amount of soil moisture during the critical periods of the crops. In contrast, the hectoliter weight recorded in the 2022/23 year increased by 2.3% compared to the 2023/24 cropping year (Table 4.10), which might be due to weather variability between the cropping years. For instance, during the 2022/23 cropping year, an additional 12 mm of rainfall was recorded, leading to a 0.4 °C increase in maximum temperatures during the 2023/24 cropping year (Table 1.2). In this context, low water stress affects hectoliter weight (Rao *et al.*, 2021), and higher temperatures also impact the hectoliter weight of wheat (Moayedi *et al.*, 2021). In this line, the previous research indicated that the hectoliter weight of barley was significantly affected by the interaction between nitrogen rates and irrigation levels (Sharma and Verma, 2010).

Starch content

Statistical analysis of the data presented in Table 4.9 indicates that irrigation intervals and the interaction effect of irrigation interval and nitrogen rates significantly affected the starch content of durum wheat at $p \leq 0.05$ during both tested years. However, the main effect of nitrogen rates did not have a significant impact on starch content at $p > 0.05$ in either year (Table 4.8).

The data clearly show that the highest starch content was recorded in plots treated with 184 kg N ha⁻¹ at the I₁ irrigation interval, followed by 138 kg N ha⁻¹ at I₁ irrigation interval, and I₂ irrigation interval under the application of 138 kg N ha⁻¹ and 184 kg N ha⁻¹. In contrast, the lowest starch content was observed with the application of 0 kg N ha⁻¹ at the I₃ irrigation interval in both production years (Table 4.9). The highest starch content was consistently recorded at the I₁ irrigation interval, followed by I₂ and I₃ intervals. Additionally, increasing the application of nitrogen rates from 0 to 184 kg ha⁻¹ resulted in a non-significant increase in the starch content of durum wheat across all irrigation intervals (Table 4.9).

However, the starch content recorded during the 2022/23 cropping year increased by 0.5% compared to that recorded during the 2023/24 cropping season, possibly due to weather variability between the two years (Table 4.9). In this regard, the previous research indicates that drought stress accelerates grain filling while reducing total starch accumulation (Lu *et al.*, 2019), and that high temperatures inhibit starch accumulation in grains (Khan *et al.*, 2020). Additionally, earlier studies have shown that the starch content of both wheat and rice is significantly affected by the interaction between nitrogen and irrigation levels (Hu *et al.*, 2023).

Protein content

The analysis of variance indicated that the main effects of nitrogen rates, irrigation intervals, and their interaction significantly affected the protein content of durum wheat at $p \leq 0.01$ in both tested years (Table 4.8).

The protein content of durum wheat ranged from 11% to 15.9% and from 11% to 16.4% during the 2022/23 and 2023/24 cropping years, respectively (Table 4.9). The higher protein content recorded at the application of 184 kg N ha⁻¹ with the I₃ interval, followed by 138 kg N ha⁻¹ at the I₃ interval, 184 kg N ha⁻¹ at the I₂ interval, and 183 kg N ha⁻¹ at the I₂ interval. Conversely, the smaller starch content recorded with the application of 0 kg N ha⁻¹ at the I₁ interval in both tested years (Table 4.9). Increasing the nitrogen application rates from 0 to 184 kg ha⁻¹ led to an increase in the protein content of durum wheat across all intervals (Table 4.9). However, the highest protein content was recorded with the I₃ interval compared to the I₁ and I₂ intervals.

The protein content recorded in the 2023/24 increased by 1.7% compared to the 2022/23 cropping year, which may be attributed to weather variability between the years. For instance, during the 2023/24 cropping season, the maximum temperatures increased by 0.4 °C compared to the 2022/23 (Table 1.2). Therefore, the increase in maximum temperature during the growing period of the crops reduced grain yield but increased the grain protein content. In this regard, previous research has also indicated that the protein content of wheat is affected by water stress and higher temperatures (Khan *et al.*, 2020; El Haddad *et al.*, 2021). Furthermore, earlier studies have shown that the starch content of wheat and rice is significantly influenced by the interaction of nitrogen and irrigation levels (Zhang *et al.*, 2017; Liu, 2023).

Table 4.9. Mean of same grain quality of the durum wheat influenced by nitrogen rates and irrigation intervals during 2022/23 and 2023/24 cropping years at DZARC.

Treatments		2022/23 cropping year				2023/24 cropping year			
Irrigation intervals	N ha ⁻¹ (kg)	Thousand	Hectoliter	Starch content (%)	Protein content (%)	Thousand	Hectoliter	Starch content (%)	Protein content (%)
		kernel weight (g)	weight (kg/hl)			kernel weight (g)	weight (kg/hl)		
I ₁	0	30 ^{de}	44 ^{fg}	67.9 ^{ab}	11 ^g	29 ^{d-f}	43 ^{fg}	67.1 ^{a-c}	11 ^g
I ₁	46	36 ^{cd}	59 ^e	70 ^{ab}	12.5 ^{e-g}	37 ^c	58 ^e	69.5 ^{a-c}	12.5 ^{ef}
I ₁	92	48 ^{ab}	72 ^{cd}	70.2 ^{ab}	13.3 ^{c-f}	47 ^{ab}	71 ^{cd}	70 ^{a-c}	13.1 ^{d-f}
I ₁	138	52 ^a	80 ^{ab}	71.3 ^a	14 ^{b-e}	51 ^a	79 ^{ab}	70.8 ^a	14.4 ^{b-d}
I ₁	184	51.1 ^{ab}	81 ^a	70.5 ^{ab}	14.8 ^{a-c}	50.7 ^a	80 ^a	71 ^a	14.7 ^{bc}
I ₂	0	30 ^{de}	40 ^{gh}	67.6 ^{ab}	12 ^{fg}	28.5 ^{ef}	38.1 ^{gh}	66.7 ^{bc}	12.2 ^{fg}
I ₂	46	33 ^{cd}	56 ^e	69.8 ^{ab}	12.9 ^{d-f}	34.5 ^{cd}	55 ^e	69.4 ^{a-c}	13 ^{d-f}
I ₂	92	47 ^{ab}	70 ^d	70 ^{ab}	13.5 ^{b-f}	46 ^{ab}	69 ^d	70 ^{a-c}	13.3 ^{c-f}
I ₂	138	51.7 ^a	75 ^{b-d}	70.2 ^{ab}	14.5 ^{a-d}	50.1 ^a	74 ^{b-d}	70.5 ^{ab}	15.3 ^{ab}
I ₂	184	50 ^{ab}	76 ^{a-c}	70.3 ^{ab}	15.1 ^{ab}	49 ^{ab}	75 ^{a-c}	70.7 ^{ab}	15.6 ^{ab}
I ₃	0	25 ^e	35 ^h	67.2 ^b	12.2 ^{fg}	23.5 ^f	33.1 ^h	66 ^c	12.2 ^{fg}
I ₃	46	31 ^{de}	45 ^{fg}	68.1 ^{ab}	13 ^{d-f}	30 ^{de}	43 ^{fg}	67.5 ^{a-c}	13.7 ^{c-e}
I ₃	92	38 ^c	47 ^f	68.4 ^{ab}	13.9 ^{b-e}	32 ^{c-e}	46 ^f	67.9 ^{a-c}	14.2 ^{b-d}
I ₃	138	47 ^{ab}	48 ^f	69.4 ^{ab}	15.8 ^a	45.5 ^{ab}	45 ^f	69 ^{a-c}	16.3 ^a
I ₃	184	45 ^b	45 ^{fg}	68.5 ^{ab}	15.9 ^a	43.5 ^b	44 ^f	68 ^{a-c}	16.4 ^a
Grand mean		40.99	58.2	69.29	13.63	39.82	56.88	68.94	13.86
CV (%)		9.80	5.77	3.34	7.19	8.68	5.90	3.55	6.23
LSD (5%)		6.7	5.5	3.85	1.63	5.76	5.6	4.08	1.44
LS		*	**	*	**	*	**	*	**

ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. Mean followed by the same letter are non-significant. LSD (%) = Listed significant different at 5% level, and CV (%) = Percentage of coefficient of variation, LS=level of significant, I₁= irrigation events per every seven days' interval per cropping year, I₂=irrigation events every ten days' interval per cropping year, I₃=irrigation events every thirteen days' interval per cropping year, N=Nitrogen fertilizer.

Gluten index

The analysis of variance revealed that both nitrogen rates and irrigation interval had a significant effect on the gluten index of durum wheat at $p \leq 0.01$ in both production years. Additionally, the interaction between nitrogen rates and irrigation frequencies significantly affected the gluten index of durum wheat at $p \leq 0.05$ during both cropping years (Table 4.10).

The highest gluten index was recorded with the interaction of 184 kg of N ha⁻¹ at the I₃ irrigation interval, followed by 138 kg of N ha⁻¹ at the I₃ irrigation interval, 184 kg of N ha⁻¹ at the I₂ irrigation interval, and 138 kg of N ha⁻¹ at the I₂ irrigation interval. Conversely, the lowest gluten index observed with the interaction of 0 kg N ha⁻¹ at the I₁ irrigation interval in both cropping years (Table 4.11). The results of the study indicated that increasing the nitrogen rate from 0 to 92 kg ha⁻¹ significantly raised the gluten index at all irrigation frequencies. However, further increases in nitrogen rates from 92 to 184 kg ha⁻¹ resulted in statistically significant changes but did not significantly affect the gluten index (Table 4.11). Accordingly, the gluten index of durum wheat increased significantly due to nitrogen fertilizer application up to a certain level for any given irrigation interval.

The gluten index of wheat flour is a criterion for defining gluten quality. It is considered weak when the gluten index is less than 30%, normal when the gluten index ranges from 30% to 80%, and strong when the gluten index is greater than 80% (Oikonomou *et al.*, 2015). Therefore, the current gluten index results ranged from normal to strong (Table 4.11).

On the other hand, the highest gluten content was recorded at the I₃ irrigation interval, followed by the I₂ and I₁ irrigation intervals, respectively. As a result, nitrogen rates under water stress conditions increased the gluten index of durum wheat. Furthermore, the gluten index recorded during the 2023/24 cropping year was 0.6% higher compared to the gluten index recorded in the 2022/23 cropping year (Table 4.11). This difference may be attributed to weather variability between cropping years. In this context, lower water stress and higher temperatures contributed to an increase in the gluten index of wheat (Sakr *et al.*, 2021; Mkhabela *et al.*, 2022). Additionally, previous research has indicated that the gluten index of wheat is significantly affected by nitrogen rates and irrigation intervals (Gagliardi *et al.*, 2020; Usman, 2020).

Table 4.10. Mean squares values of gluten contents, gluten index and SDS-sedimentation of durum wheat affected by nitrogen rates and irrigation intervals and during 2022/23 and 2023/24 cropping years at DZARC.

Year	Source of variation	DF	Dry gluten content (%)	Wet gluten content (%)	Gluten index (%)	SDS-Sedimentation (ml)
2022/23	Irrigation (I)	2	3.9*	46.0*	78.9**	76.7**
	Nitrogen (N)	4	35.4**	218.1**	327.4**	258.8**
	I*N	8	0.2*	6.7**	11.6*	3.1*
	Error (I*N)	24	0.7	1.5	9.9	4.4
	Grand mean		11.57	30.32	78.88	41.29
	LSD (5%)		1.44	2.04	5.24	3.52
	CV (%)		7.47	4.03	3.98	5.11
2023/24	Irrigation (I)	2	7.6*	59.7*	116.1**	80.1**
	Nitrogen (N)	4	35.0**	218.1**	327.4**	257.5**
	I*N	8	0.1*	6.7**	11.6*	2.9*
	Error(I*N)	24	0.5	2.0	9.0	4.7
	Grand mean		11.87	30.79	79.38	41.5
	LSD (5%)		1.21	2.36	5.00	3.63
	CV(%)		6.14	4.59	3.78	5.24

*ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. DF= Degrees of freedom, LSD = List significant different and CV (%) = Percentage of coefficient of variation.*

Gluten contents

The mean square values of the results indicated that the main effects of nitrogen rates and irrigation intervals significantly influenced the dry and wet gluten contents of durum wheat at $p \leq 0.05$ and $p \leq 0.01$, both production seasons. Furthermore, the interaction effects of nitrogen rates and irrigation frequencies had a significant impact on the dry and wet gluten contents of durum wheat at $p \leq 0.05$ and $p \leq 0.01$ during both cropping years (Table 4.10).

The mean performance showed that the highest dry and wet gluten contents were observed with the interaction of 184 kg of N ha⁻¹ and the I₃ irrigation interval, while the lowest values were recorded with the interaction of 0 kg N ha⁻¹ and the I₁ irrigation interval during both cropping years (Table 4.11). The current research findings demonstrated that applying nitrogen rates, increased from 0 to 184 kg ha⁻¹, correspondingly elevated the dry and wet gluten contents of durum wheat at all irrigation intervals. This phenomenon may be attributed to soil moisture stress at the I₃ irrigation interval when compared to the I₁ and I₂ irrigation intervals during the critical growth period for the crops.

In this line, the previous research finding had indicated that water stress can enhance the gluten contents of wheat (Rao *et al.*, 2021; Sheng *et al.*, 2022). Conversely, the dry and wet gluten contents recorded in the 2023/24 cropping year increased by 2.3% compared to those in the 2022/23 cropping year (Table 4.11). This increase may be attributed to weather variability between cropping years. For instance, during the 2023/24 cropping year, there was a recorded decrease of 12 mm in rainfall and an increase of 0.4 °C in maximum temperatures compared to the 2022/23 cropping year (Table 1.2). In this regard, lower water stress and higher temperatures contributed to increased gluten contents in wheat (Olckers *et al.*, 2022). Additionally, other prior research findings have also indicated that the dry and wet gluten contents of wheat are significantly affected by nitrogen rates and irrigation frequencies (Stepien and Wojtkowiak, 2019; Hao *et al.*, 2023).

Sodium dodecyl sulfate (SDS) sedimentation

The analysis of variance indicated that the main effects of nitrogen rates and irrigation interval had significantly affected the SDS sedimentation of durum wheat at $p \leq 0.01$ in both production years. Additionally, the interaction between nitrogen rates and irrigation frequencies had a significant effect on the SDS sedimentation of durum wheat at $p \leq 0.05$ in both years (Table 4.10).

The results of the study indicated that the highest SDS sedimentation was recorded with the interaction of 184 kg N ha⁻¹ at the I₃ irrigation interval, while the lowest SDS sedimentation was observed with 0 kg N ha⁻¹ at the I₁ irrigation interval in both production years (Table 4.11). The mean performance results showed that increasing the nitrogen rate from 0 to 92 kg ha⁻¹ significantly enhanced the SDS sedimentation of durum wheat at all irrigation interval s. In contrast, increasing the nitrogen rate from 92 to 184 kg ha⁻¹ also numerically increased the SDS sedimentation, but this increase had not significant different (Table 4.11).

Moreover, the I₃ irrigation interval resulted in higher SDS sedimentation compared to the I₁ and I₂ irrigation intervals in both production years. This could be attributed to inadequate soil moisture stress at the I₃ irrigation interval relative to I₁ and I₂ during the critical growth period of the crops. In this line, previous research also indicated that SDS sedimentation in wheat is significantly influenced by nitrogen rates and irrigation interval (Kumar *et al.*, 2018; El Chami *et al.*, 2023).

Table 4.11. Mean of gluten contents, gluten index and SDS-sedimentation of the durum wheat affected by nitrogen rates under different irrigation intervals during 2022/23 and 2023/24 cropping years at DZARC

Treatments		2022/23 cropping year				2023/24 cropping year			
Irrigation intervals	N ha ⁻¹ (kg)	Dry gluten (%)	Wet gluten (%)	Gluten index (%)	SDS-Sediment (ml)	Dry gluten (%)	Wet gluten (%)	Gluten index (%)	SDS-Sediment (ml)
I ₁	0	8.5 ^f	19 ^g	69 ^g	31 ⁱ	8.6 ^g	19.2 ^g	69.5 ⁱ	31.2 ⁱ
I ₁	46	9.5 ^{d-f}	26 ^e	74 ^{e-g}	38 ^{fg}	10 ^{ef}	26.7 ^e	74 ^{g-i}	38.2 ^{fg}
I ₁	92	12 ^{bc}	30.4 ^d	78 ^{c-e}	41 ^{d-f}	11.1 ^{de}	31.5 ^{cd}	78 ^{e-g}	40.2 ^{d-f}
I ₁	138	12.9 ^{ab}	33.2 ^{ab}	80.5 ^{bc}	43 ^{cd}	13 ^{bc}	33.4 ^{a-c}	81 ^{c-e}	43.2 ^{cd}
I ₁	184	13 ^{ab}	34.3 ^a	80.7 ^{bc}	46 ^{bc}	13.1 ^{bc}	34.5 ^{ab}	82 ^{c-e}	46.3 ^{bc}
I ₂	0	9 ^{ef}	22 ^f	70 ^{fg}	34 ^{hi}	9.1 ^{fg}	22.5 ^f	71 ^{hi}	34.2 ^{hi}
I ₂	46	10 ^{de}	30 ^d	75 ^{d-f}	39 ^{ef}	10.3 ^{ef}	30.6 ^d	75.5 ^{f-h}	39.3 ^{ef}
I ₂	92	12.5 ^{ab}	31 ^{cd}	80 ^{b-d}	42 ^{de}	12.1 ^{cd}	32.7 ^{b-d}	80 ^{d-f}	41.2 ^{d-f}
I ₂	138	13 ^{ab}	34 ^{ab}	81 ^{bc}	43.4 ^{cd}	13.3 ^{a-c}	34.5 ^{ab}	84.5 ^{b-d}	43.6 ^{cd}
I ₂	184	13.3 ^{ab}	34.9 ^a	85 ^{ab}	49 ^{ab}	13.5 ^{ab}	34.8 ^{ab}	85.5 ^{a-c}	46.3 ^{bc}
I ₃	0	9.1 ^{ef}	26 ^e	73 ^{e-g}	35 ^{gh}	9.4 ^{fg}	26.2 ^e	73.5 ^{g-i}	35.3 ^{gh}
I ₃	46	10.6 ^{cd}	32 ^{b-d}	76 ^{c-e}	40 ^{d-f}	12.8 ^{bc}	30.7 ^d	77 ^{e-g}	42.3 ^{de}
I ₃	92	12.9 ^{ab}	33 ^{a-c}	84 ^{ab}	42 ^{de}	13.6 ^{ab}	33.2 ^{bc}	80.7 ^{c-e}	42.4 ^{de}
I ₃	138	13.4 ^{ab}	34 ^{ab}	88 ^a	46 ^{bc}	13.9 ^{ab}	35.6 ^a	89 ^{ab}	49.3 ^{ab}
I ₃	184	13.9 ^a	35 ^a	89 ^a	50 ^a	14.4 ^a	35.7 ^a	90 ^a	50.2 ^a
Grand mean		11.57	30.32	78.88	41.29	11.87	30.78	79.38	41.5
CV (%)		7.47	4.03	3.98	5.11	6.14	4.59	3.78	5.24
LSD (5%)		1.44	2.04	5.24	3.52	1.21	2.36	5.00	3.63
LS		*	**	*	*	*	**	*	*

ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. Mean followed by the same letter are non-significant. LSD (%) = Listed significant different at 5% level, and CV (%) = Percentage of coefficient of variation, LS=level of significant, I₁= irrigation events per every seven days interval per cropping year, I₂=irrigation events every ten days interval per cropping year, I₃=irrigation events every thirteen days interval per cropping year, N=Nitrogen fertilizer.

4.3.4. Nitrogen Utilization and Use Efficiency of Durum Wheat as Influenced by Nitrogen Rates and Irrigation Frequencies.

4.3.4.1. Nitrogen use and utilization efficiency

Nitrogen-use efficiency

The nutrient-use efficiency of plants depends on their ability to efficiently absorb nutrients from the soil, as well as on the storage, mobilization, and remobilization of nutrients, nutrient metabolism within the plant, and environmental factors (Adhikari *et al.*, 2023). The analysis of variance indicated that the main effects of nitrogen rates, irrigation interval, and their interaction significantly affected the nitrogen-use efficiency of durum wheat at $p \leq 0.01$ in both production years (Table 4.12).

The current research results indicated that the nitrogen-use efficiency ranged from 8.7 to 62 kg kg⁻¹ and from 13.6 to 58.7 kg kg⁻¹ in the 2022/23 and 2023/24 cropping years, respectively, as shown in Table 4.13. The highest nitrogen-use efficiency recorded with the application of 92 kg N ha⁻¹ at the I₁ irrigation interval, followed by 92 kg N ha⁻¹ at the I₂ irrigation interval, 138 kg N ha⁻¹ at the I₁ irrigation interval, 46 kg N ha⁻¹ at the I₁ irrigation interval and 138 kg N ha⁻¹ at the I₂ irrigation interval. In contrast, the lowest nitrogen-use efficiency was recorded with an application of 184 kg N ha⁻¹ at the I₃ irrigation interval in both cropping years (Table 4.13).

As a result, the nitrogen-use efficiency of durum wheat across the nitrogen rates at 46 and 138 kg N ha⁻¹ under the I₁ irrigation interval and nitrogen rates of 46, 92 and 138 kg N ha⁻¹ at I₂ irrigation intervals did not significantly differ, while the nitrogen-use efficiency recorded with 184 kg N ha⁻¹ at I₁ and I₂ irrigation intervals had not significant different (Table 4.13). On the other hand, the nitrogen-use efficiency recorded at the application of I₃ irrigation interval with 46, 138 and 184 kg N ha⁻¹ rates were significantly different from the I₁ and I₂ irrigation intervals except 0 kg N ha⁻¹ (Table 4.13). Therefore, nitrogen-use efficiency in durum wheat is not only affected by nitrogen rate but also by irrigation frequency, potentially due to soil moisture variability during the mass flow process at critical growth stages.

Additionally, the nitrogen-use efficiency recorded in the 2022/23 cropping year was 1.8% higher compared to the 2023/24 cropping year, which may be attributed to differences in higher temperature and soil moisture variability during the crop's growing period. For instance, during the 2022/23 cropping year, an additional 12 mm of rainfall recorded, coinciding with a 0.4 °C increase in temperatures in the 2023/24 cropping year (Table 1.2). Consequently, nitrogen-use efficiency in durum wheat decreased when nitrogen rates increased from 92 to 184 kg N ha⁻¹, likely due to the lesser increase in grain yield relative to the amount of nitrogen used. Furthermore, several previous studies have indicated that nitrogen-use efficiency in wheat and barley is affected by both nitrogen rate and irrigation frequency (Kumar *et al.*, 2018; Hao *et al.*, 2023; Khan *et al.*, 2023).

Table 4.121. Mean squares values of nitrogen-use efficiency, agronomic efficiency and physiological efficiency influenced by nitrogen rates and irrigation intervals during 2022/23 and 2023/24 cropping years at DZARC.

Year	S.V	DF	Nitrogen-use efficiency (kg/kg)	Agronomic Efficiency (kg/kg)	Physiological Efficiency (kg/kg)
2022/23	Replication (R)	2	5.17	10.34	2.61
	Irrigation (I)	2	3646.64**	1651.5**	3044.3**
	Error (R*I)	4	3.70	9.29	2.26
	Nitrogen (N)	4	2725.82**	1495.2**	9550.8**
	I*N	8	284.12**	214.8**	780.7**
	Error (R*I*N)	24	16.05	5.16	37.9
	Grand mean		29.28	20.86	46.92
	LSD (5%)		6.33	4.56	9.40
	CV _(R*I*N) (%)		13.68	10.89	13.31
2023/24	Replication (R)	2	1.15	11.44	29.61
	Irrigation (I)	2	1990.8**	1304.29**	6275.0**
	Error (R*I)	4	1.1	11.84	29.61
	Nitrogen(N)	4	2650.4**	1799.69**	8755.68**
	I*N	8	198.5**	165.64**	922.60**
	Error (R*I*N)	24	16.79	9.05	29.61
	Grand mean		28.75	22.71	45.16
	LSD (5%)		6.26	5.67	9.80
	CV _(R*I*N) (%)		14.25	22.71	12.05

ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. *DF*= Degrees of freedom, *LSD* = List significant different and *CV (%)* = Percentage of coefficient of variation.

Table 4.13. Mean of nitrogen-use efficiency, agronomic efficiency and physiological efficiency of the durum wheat influenced by nitrogen rates and irrigation intervals during 2022/23 and 2023/24 cropping years at DZARC.

Treatments			2022/23 cropping year			2023/24 cropping year		
Irrigation intervals	N (kg)	ha ⁻¹	Nitrogen-use efficiency (kg/kg)	Agronomic Efficiency (kg/kg)	Physiological Efficiency (kg/kg)	Nitrogen-use efficiency (kg/kg)	Agronomic Efficiency (kg/kg)	Physiological Efficiency (kg/kg)
I ₁	0		0.0 ^f	-	-	0 ⁱ	-	-
I ₁	46		51.8 ^b	19.6 ^{de}	25.42 ^{fg}	43.5 ^{cd}	26.1 ^{de}	30.39 ^f
I ₁	92		62.0 ^a	45.7 ^a	86.96 ^{ab}	58.7 ^a	48.9 ^a	94.83 ^a
I ₁	138		50.7 ^b	39.9 ^b	93.97 ^a	48.6 ^{bc}	42.03 ^{bc}	89.61 ^{ab}
I ₁	184		37.0 ^c	28.8 ^c	77.33 ^{bc}	34.2 ^{ef}	29.3 ^d	75.33 ^{cd}
I ₂	0		0.0 ^f	-	-	0 ⁱ	-	-
I ₂	46		45.7 ^b	23.9 ^d	19.93 ^g	39.1 ^{de}	23.9 ^{de}	30.72 ^f
I ₂	92		52.2 ^b	41.3 ^{ab}	79.9 ^{bc}	52.2 ^b	44.6 ^{ab}	97.45 ^a
I ₂	138		47.8 ^b	40.6 ^b	91.5 ^a	45.7 ^c	38.4 ^c	81.78 ^{bc}
I ₂	184		34.8 ^c	29.3 ^c	75.91 ^c	30.9 ^f	27.2 ^{de}	69.39 ^d
I ₃	0		0.0 ^f	-	-	0 ⁱ	-	-
I ₃	46		21.7 ^d	15.2 ^{ef}	33.89 ^{ef}	23.9 ^g	15.2 ^f	17.18 ^g
I ₃	92		13.0 ^e	9.8 ^{gh}	39.02 ^{de}	16.3 ^h	12.0 ^f	18.59 ^g
I ₃	138		13.8 ^e	11.6 ^{fg}	45.7 ^d	24.6 ^g	21.6 ^e	43.2 ^e
I ₃	184		8.7 ^e	7.1 ^h	34.28 ^{ef}	13.6 ^h	11.4 ^f	28.9 ^f
Grand mean			29.28	20.86	46.92	28.75	22.71	45.16
CV (%)			13.68	10.89	13.13	12.86	13.24	12.05
LSD (5%)			6.33	4.56	9.4	6.26	5.67	9.8
LS			**	**	**	**	**	**

ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. Mean followed by the same letter are non-significant. LSD (%) = Listed significant different at 5% level, and CV (%) = Percentage of coefficient of variation, LS=level of significant, I₁= irrigation events per every seven days' interval per cropping year, I₂=irrigation events every ten days' interval per cropping year, I₃=irrigation events every thirteen days' interval per cropping year, N=Nitrogen fertilizer.

Agronomic efficiency

Agronomic efficiency refers to the effectiveness of applied nutrients in increasing grain or biomass yield (Adhikari *et al.*, 2023). The current analysis of variance revealed that the main effects of nitrogen rates, irrigation interval, and their interaction significantly influenced the agronomic efficiency of durum wheat at $p \leq 0.01$ in both production years (Table 4.12).

The mean performance values of agronomic efficiency recorded during the 2022/23 and 2023/24 cropping years ranged from 7.1 to 45.7 kg kg⁻¹ and 11.4 to 48.9 kg kg⁻¹. The application of 92 kg N ha⁻¹ at the I₁ irrigation interval resulted in the higher agronomic efficiency, followed by 92 kg N ha⁻¹ at the I₂ irrigation interval and 138 kg N ha⁻¹ at both I₁ and I₂ irrigation intervals. Conversely, the lower agronomic efficiency was observed with the application of 184 kg N ha⁻¹ at the I₂ irrigation interval in both cropping years (Table 4.13). Notably, increasing the nitrogen rate from 0 to 92 kg ha⁻¹ enhanced the agronomic efficiency, while increasing the nitrogen rates from 92 to 184 kg ha⁻¹ led to a decrease in the agronomic efficiency of durum wheat in both seasons (Table 4.13).

Additionally, the agronomic efficiency recorded at the I₁ irrigation interval was higher compared to the I₂ and I₃ irrigation intervals, although no significant difference was observed between the I₂ and I₃ intervals (Table 4.13). Furthermore, the agronomic efficiency for the 2023/24 cropping year was 8.1% higher compared to that recorded in the 2022/23 cropping year, which could be attributed to weather variability between the tested cropping years (Table 1.2). Ultimately, this study indicated that the agronomic efficiency of durum wheat was significantly affected by the interaction of nitrogen rates and irrigation interval in the study area. In this context, previous research has also indicated that nitrogen rates and irrigation interval impact the agronomic efficiency of wheat (Si *et al.*, 2020; Boulelouah *et al.*, 2022; Abdelkader *et al.*, 2023).

Physiological efficiency

The current research results indicate that the main effects of nitrogen rates, irrigation interval, and their interaction significantly impacted the physiological efficiency of durum wheat at $p \leq 0.01$ during the 2022/23 and 2023/24 production years (Table 4.12).

The physiological efficiency recorded during the 2022/23 and 2023/24 cropping years ranged from 19.93 to 93.97 kg kg⁻¹ and from 17.18 to 97.45 kg kg⁻¹, respectively (Table 4.13). The application of 138 kg N ha⁻¹ at the I₁ irrigation interval produced the maximum physiological efficiency (93.97 kg kg⁻¹), while the minimum physiological efficiency (19.93 kg kg⁻¹) observed with the application of 46 kg N ha⁻¹ at the I₂ irrigation interval during the 2022/23 cropping year (Table 4.13). Similarly, during the 2023/24 cropping year, the plot that received 92 kg N ha⁻¹ at the I₂ irrigation interval recorded the maximum physiological efficiency (97.45 kg kg⁻¹) of durum wheat, whereas the minimum (17.18 kg kg⁻¹) observed with the application of 46 kg N ha⁻¹ at the I₃ irrigation interval during the 2022/23 cropping year (Table 4.13).

However, increasing nitrogen rates from 0 to 138 kg ha⁻¹ enhanced physiological efficiency, while increasing from 138 to 184 kg ha⁻¹ decreased the physiological efficiency of durum wheat in both years across all irrigation intervals (Table 4.13). Additionally, the physiological efficiency recorded in the 2022/23 cropping year was 8.1% higher than that registered in the 2023/24 cropping year, likely due to weather variability between the two cropping years (Table 1.2). This study indicates that the physiological efficiency of durum wheat was significantly affected by nitrogen rates and irrigation interval. Furthermore, previous research has shown that nitrogen rates and irrigation interval impact the physiological efficiency of wheat and other crops (Boyle, 2015; Zamudio *et al.*, 2015; Si *et al.*, 2020 & 2021).

Agro physiological efficiency

The analysis of variance revealed that the main effects of nitrogen rates, irrigation interval, and the interaction between nitrogen and irrigation interval significantly affected the agro-physiological efficiency of durum wheat at $p \leq 0.01$ in both production years (Table 4.14).

Agro-physiological efficiency was determined by taking the ratio of nutrient accumulation in grain and straw from fertilized plots, subtracting the nutrient accumulation of grain and straw in unfertilized plots, dividing by the quantity of nutrient applied, and multiplying by one hundred. The current research findings indicated that the agro-physiological efficiency ranged from 7.83 to 39.71 kg kg⁻¹ during the 2022/23 cropping year and from 7.71 to 44.59 kg kg⁻¹ during the 2023/24 cropping year (Table 4.15). The higher and lower agro-physiological efficiencies were

recorded with the application of 138 kg N ha⁻¹ at I₂ irrigation interval and 46 kg N ha⁻¹ at I₃ irrigation interval, respectively, during the 2022/23 cropping year (Table 4.15).

Similarly, during the 2023/24 cropping year, the higher and lower agro-physiological efficiencies were recorded with the application of 92 kg N ha⁻¹ at I₂ irrigation interval and 0 kg N ha⁻¹ at I₃ irrigation interval, respectively (Table 4.15). On the other hand, the agro-physiological efficiencies recorded with the applications of I₁ and I₂ irrigation intervals were not significantly different from each other. However, the agro-physiological efficiency recorded with the application of I₃ irrigation interval was significantly different from that of I₁ irrigation interval at any rate of nitrogen fertilizer (Table 4.15).

As a result, both nitrogen rates and irrigation intervals significantly influenced the agro-physiological efficiency of durum wheat. Moreover, the agro-physiological efficiency recorded during the 2023/24 cropping year increased by 10.9% compared to that recorded during the 2022/23 cropping year, which may be attributed to variations in weather conditions during the cropping years (Table 1.2). In this regard, previous research has also indicated that the agro-physiological efficiency of wheat and maize crops was affected by nitrogen fertilizer and irrigation frequency (Fresew Belete *et al.*, 2018; Ghimire, 2020; Mashiqa *et al.*, 2021; Sangwan *et al.*, 2022).

Apparent recovery efficiency

The main square value indicated that the effects of nitrogen rates, irrigation interval, and their interaction had a significant impact on the apparent recovery efficiency of durum wheat at $p \leq 0.01$ in both production years (Table 4.14).

The mean performance results showed a decrease in apparent recovery efficiency as nitrogen rates increased from 0 to 184 kg ha⁻¹ (Table 4.15). The highest apparent recovery efficiency was recorded with the application of 46 kg N ha⁻¹ at the I₂ irrigation interval, followed by 46 kg N ha⁻¹ at the I₁ irrigation interval, 46 kg N ha⁻¹ at the I₃ irrigation interval, and 92 kg N ha⁻¹ at the I₁ irrigation interval, respectively. Conversely, the lowest apparent recovery efficiency was observed with the application of 184 kg N ha⁻¹ at the I₃ irrigation interval during the 2022/23

cropping year (Table 4.16). In the 2023/24 cropping year, the highest apparent recovery efficiency was noted with the application of 46 kg N ha⁻¹ at the I₁ irrigation interval, followed by 46 kg N ha⁻¹ at the I₂ irrigation interval, 46 kg N ha⁻¹ at the I₃ irrigation interval, and 92 kg N ha⁻¹ at the I₃ irrigation interval, respectively. The lowest apparent recovery efficiency was again recorded with the application of 184 kg N ha⁻¹ at the I₃ irrigation interval (Table 4.15). Furthermore, the apparent recovery efficiency recorded in the 2022/23 cropping year increased by 4.3% compared to that of the 2023/24 cropping year, which could be attributed to variability in weather conditions during the cropping years (Table 1.2). In this context, previous research has also indicated that the apparent recovery efficiency of wheat is influenced by nitrogen fertilizer and irrigation interval (Kumar *et al.*, 2018; Getinet Adugna and Wassie Haile, 2019; Tabak *et al.*, 2020).

Table 4.142. Mean squares values of agro physiological efficiency, apparent recovery efficiency and utilization efficiency influenced by nitrogen rates and irrigation intervals during 2022/23 and 2023/24 cropping years at DZARC.

Year	S.V	DF	Agro physiological Efficiency (kg/kg)	Apparent Recovery Efficiency (%)	Utilization Efficiency (%)
2022/23	Replication (R)	2	0.44	341.6	2.7
	Irrigation (I)	2	1087.05**	4519.6**	5516.7**
	Error (R*I)	4	0.38	88.6	3.2
	Nitrogen (N)	4	1442.4**	59875.4**	10105.5**
	I*N	8	198.66**	3106.6**	940.6**
	Error	24	6.06	191.3	31.1
	Grand mean		17.66	107.75	55.49
	LSD (5%)		3.76	22.81	8.58
CV _(R*I*N) (%)		13.93	12.84	10.04	
2023/24	Replication (R)	2	11.93	331.7	41.8
	Irrigation (I)	2	1395.22**	1349.9*	6442.7
	Error (R*I)	4	11.93	266.7	41.8
	Nitrogen(N)	4	1669.34**	41704.6**	9078.6**
	I*N	8	180.01**	335.3*	822.02**
	Error (R*I*N)	24	6.60	117.3	41.67
	Grand mean		20.50	101.7	51.09
	LSD (5%)		5.17	23.0	11.6
CV _(R*I*N) (%)		12.53	10.65	12.63	

ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. *DF*= Degrees of freedom, *LSD* = List significant different and *CV* (%) = Percentage of coefficient of variation.

Utilization efficiency

The analysis of variance indicated that the main effects of nitrogen rates, irrigation interval, and their interaction significantly impacted the utilization efficiency of durum wheat at $p \leq 0.01$ in both production years (Table 4.14).

The highest utilization efficiency was recorded with the application of 92 kg N ha⁻¹ at the I₁ irrigation interval, followed by the application of 138 kg N ha⁻¹ at the I₁ interval, 92 kg N ha⁻¹ at the I₂ interval, and 138 kg N ha⁻¹ at the I₂ irrigation interval. Conversely, the lowest utilization efficiency was observed with the application of 184 kg N ha⁻¹ at the I₃ interval during the 2022/23 cropping year (Table 4.15). Similarly, during the 2023/24 cropping year, the highest utilization efficiency was registered with the application of 92 kg N ha⁻¹ at the I₁ irrigation interval, followed by the application of 92 kg N ha⁻¹ at the I₂ interval, 138 kg N ha⁻¹ at the I₁ irrigation interval, and 138 kg N ha⁻¹ at the I₂ interval. The lowest efficiency was recorded with the application of 184 kg N ha⁻¹ at the I₃ interval (Table 4.15). However, increasing the nitrogen rate from 0 to 92 kg N ha⁻¹ improved the utilization efficiency, while rates above 92 kg N ha⁻¹ caused a decline in the efficiency of durum wheat. Furthermore, the utilization efficiency recorded in the 2022/23 cropping year increased by 7.9% compared to the 2023/24 cropping year, possibly due to weather variability during the cropping years (Table 1.2). In line with this, previous research has also indicated that the utilization efficiency of wheat is influenced by nitrogen fertilizer and irrigation frequency (De Oliveira *et al.*, 2020; Liu *et al.*, 2024).

Table 4.3. Mean of agro physiological efficiency, apparent recovery efficiency and utilization efficiency of the durum wheat influenced by nitrogen rates and irrigation intervals in 2022/23 and 2023/24 cropping years at DZARC

Treatments		2022/23 cropping year			2023/24 cropping year		
Irrigation intervals	N ha ⁻¹ (kg)	Agro physiological Efficiency (kg/kg)	Apparent Recovery Efficiency (%)	Utilization Efficiency (%)	Agro physiological Efficiency (kg/kg)	Apparent Recovery Efficiency (%)	Utilization Efficiency (%)
I ₁	0	-	-	-	-	-	-
I ₁	46	8.92 ^d	219.24 ^b	55.72 ^e	19.21 ^e	197.43 ^a	59.99 ^{de}
I ₁	92	34.25 ^{bc}	133.28 ^d	115.9 ^a	41.23 ^{ab}	118.6 ^c	112.5 ^a
I ₁	138	36.75 ^{ab}	108.44 ^{ef}	101.9 ^b	39.6 ^{ab}	106.17 ^{cd}	95.14 ^{bc}
I ₁	184	30.22 ^c	95.33 ^{fg}	73.71 ^c	32.99 ^{cd}	88.95 ^d	67.01 ^d
I ₂	0	-	-	-	-	-	-
I ₂	46	7.83 ^d	305.4 ^a	60.87 ^{de}	13.96 ^{fg}	171.2 ^b	52.6 ^e
I ₂	92	34.92 ^b	118.3 ^{de}	94.56 ^b	44.59 ^a	99.93 ^{cd}	97.38 ^b
I ₂	138	39.71 ^a	102.96 ^{e-g}	94.18 ^b	37.5 ^{bc}	102.43 ^{cd}	83.77 ^c
I ₂	184	33.06 ^{bc}	88.78 ^{fg}	67.39 ^{cd}	31.54 ^d	86.15 ^d	59.78 ^{de}
I ₃	0	-	-	-	-	-	-
I ₃	46	9.49 ^d	160.37 ^c	54.35 ^{ef}	7.71 ⁱ	197.4 ^a	33.92 ^f
I ₃	92	9.76 ^d	100.28 ^{e-g}	39.13 ^g	8.02 ^{hi}	149.07 ^b	27.71 ^f
I ₃	138	11.43 ^d	101.43 ^{e-g}	46.37 ^{fg}	18.92 ^{ef}	114.91 ^c	49.64 ^e
I ₃	184	8.57 ^d	82.44 ^g	28.26 ^h	12.3 ^{gh}	93.09 ^d	26.9 ^f
Grand mean		17.66	107.75	55.49	20.5	101.7	51.08
CV (%)		13.93	12.84	10.04	12.53	10.65	12.63
LSD (5%)		3.76	22.81	8.57	5.17	23.0	11.6
LS		**	**	**	**	*	**

ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. Mean followed by the same letter are non-significant. LSD (%) = Listed significant different at 5% level, and CV (%) = Percentage of coefficient of variation, LS=level of significant, I₁= irrigation events per every seven days' interval per cropping year, I₂=irrigation events every ten days' interval per cropping year, I₃=irrigation events every thirteen days' interval per cropping year, N=Nitrogen fertilizer.

4.3.5. Partial Budget

An estimate of the economic aspect of the present study has been computed, and the results, along with all relevant calculations and interpretations, are presented in Table 4.16. The results of the economic analysis indicate that the highest net profit (Birr 411,795.00) was obtained from plots treated with 138 kg N ha⁻¹ at the I₁ irrigation interval. This was followed by plots treated with 184 kg N ha⁻¹ at the I₁ irrigation interval, 138 kg N ha⁻¹ at the I₂ irrigation interval, and 184 kg N ha⁻¹ at the I₂ irrigation interval, respectively. In contrast, the control plot at the I₃ irrigation interval recorded the lowest economic benefit (166.7%) (Table 4.16). The primary reason for the lower economic benefit of the I₃ irrigation interval with no nitrogen fertilizer application compared to the other tested treatments could be attributed to low nitrogen levels and insufficient water in the soil, which restricted overall growth, development, and ultimately reduced the crop's grain yield.

On the other hand, the highest benefit-cost ratio was noted for the application of 138 kg N ha⁻¹ at the I₂ irrigation interval, whereas the control plot at the I₃ irrigation interval yielded a lower benefit-cost ratio (Table 4.16). Among the irrigated treatments with the same nitrogen fertilizer rates, the application of I₂ irrigation interval produced a higher benefit-cost ratio compared to the I₁ and I₃ irrigation intervals. Additionally, the Marginal Rate of Return (MRR %) showed that the highest MRR % was recorded for the application of I₂ irrigation interval, while the lowest MRR % was obtained from the control plot at the I₃ irrigation interval (Table 4.16). As a result, the application of 138 kg N ha⁻¹ at the I₂ irrigation interval was deemed economically feasible (recommended) for durum wheat production in the study area.

Table 4.164. Economic analysis of wheat as affected by nitrogen rate under irrigated production system.

Treatment		Yield (kg ha ⁻¹)				Gross	Total	Net	Benefit	Marginal
Irrigation intervals	Nitrogen rates (Kg ha ⁻¹)	Yield (kg ha ⁻¹)		Income (Birr ha ⁻¹)		income (Birr ha ⁻¹)	Expenditure (Birr ha ⁻¹)	income (Birr ha ⁻¹)	Cost Ratio	Rate of Return (%)
		Grain	Straw	Grain	Straw					
I ₁	0	1200	1555	54000	23325	77325	18000	59325	3.3	329.58
I ₁	46	2252	3165	101340	47475	148815	21500	123815	5.8	575.88
I ₁	92	5549	7710	249705	115650	365355	25000	333355	13.3	1333.42
I ₁	138	6851	9500	308295	142500	450795	28500	411795	14.4	1444.89
I ₁	184	6545	9150	294525	137250	431775	32000	385775	12.1	1205.55
I ₂	0	850	1070	38250	16050	54300	13000	41300	3.2	317.69
I ₂	46	1953	2580	87885	38700	126585	16500	106585	6.5	645.97
I ₂	92	4801	5950	216045	89250	305295	20000	278295	13.9	1391.48
I ₂	138	6306	7850	283770	117750	401520	23500	367520	15.6	1563.91
I ₂	184	6050	7570	272250	113550	385800	27000	344800	12.8	1277.04
I ₃	0	351	725	15795	10875	26670	10000	16670	1.7	166.70
I ₃	46	1050	2055	47250	30825	78075	13500	61075	4.5	452.41
I ₃	92	1353	2800	60885	42000	102885	17000	78885	4.6	464.03
I ₃	138	2654	5050	119430	75750	195180	20500	164180	8.0	800.88
I ₃	184	2049	4100	92205	61500	153705	24000	115705	4.8	482.10

*I*₁= irrigation events per every seven days' interval per cropping year, *I*₂=irrigation events every ten days' interval per cropping year, *I*₃=irrigation events every thirteen days' interval per cropping year. Price = 45 birr / kilogram of grain and Straw = 15birr/ kilogram of straw, Fertilizer cost = 35 birr / kilogram of Urea, Irrigated cost per events = 1000 birr/ events, Total irrigated cost (*I*₁= 18000, *I*₂ = 13000 and *I*₃=10,000 birr)

4.4. CONCLUSION

The study evaluated the effects of nitrogen rate, irrigation interval, and their interaction on phenology, growth, yield-related traits, yield, grain quality, and nitrogen use and utilization efficiency of durum wheat during the 2022/23 and 2023/24 cropping years. The results of the statistical analysis indicated that almost all the studied parameters were significantly affected by the main effects of nitrogen rate, irrigation interval, and their interaction. It was concluded that the application of 184 kg N ha⁻¹ at the I₁ irrigation interval significantly influenced yield and yield-related parameters during both production years. However, the results for yield and yield-related parameters under the application of 184 kg N ha⁻¹ at the I₁ irrigation interval did not significantly differ from those recorded under 138 kg N ha⁻¹ at the I₂ irrigation interval during the 2022/23 and 2023/24 cropping seasons. The highest values for grain quality, including protein and gluten content, were recorded under the application of 184 kg N ha⁻¹ at the I₃ irrigation interval. Nevertheless, the protein content resulting from the application of the I₃ irrigation interval at any nitrogen rates was significantly different from those at the I₁ irrigation interval, while it did not significantly differ from those under the application of the I₂ irrigation interval at certain nitrogen rates. The economic analysis also indicated that the maximum benefit-cost ratio (BCR) of 15.6% and marginal rate of return (MRR) of 1563.91% were observed in plots receiving 138 kg N ha⁻¹ with a ten-day irrigation interval (I₂) per cropping year. Therefore, the application of 138 kg N ha⁻¹ at the I₂ irrigation interval was deemed economically feasible for durum wheat production in the study area and in regions with similar soil and agro-climatic conditions.

4.5. REFERENCE

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5. CALIBRATION AND EVALUATION OF DSSAT-CERES-WHEAT MODEL FOR SIMULATING GROWTH AND YIELD OF DURUM WHEAT (*Triticum turgidum* L.) UNDER IRRIGATED ENVIRONMENT IN CENTRAL ETHIOPIA.

ABSTRACT

In order to evaluate the applicability of the DSSAT-CERES model, calibration and evaluation of the model is a mandatory step for wheat. For model calibration and evaluation purposes a field experiment of durum wheat cultivars simulation under irrigated growing environment was conducted during the 2018/19, 2019/20, 2020/21, 2021/22 2022/23 growing seasons at Deber Zeit in central Ethiopia. The model was calibrated using two years of field experiments (2018/19, and 2019/20) to capture wheat growth and yield. Evaluation of the model was conducted using three years of field experiments (2020/21, 2021/22 and 2022/23). However, to use the successful prediction of the production states of the crops, cultivar specific genetic coefficients are required. Thus, the current research activity was calibration and evaluation of three durum wheat cultivars under central Ethiopia environmental conditions for the following objectives i) to generate the genetic coefficient of the three durum wheat cultivars required for running of DSSAT model in Central Ethiopian condition and ii) to evaluation DSSAT crop model for simulation of growth and yield of durum wheat cultivars. The DSSAT-CERES-Wheat simulation model was calibrated and evaluation against the experimental data which was conducted under the irrigated environment. The performance of evaluation of the DSSAT-CERES-Wheat model revealed that the model was able to simulate crop phenology (days to physiological maturity) and yield (grain, biomass, and straw) accurately, with lower percent of normalized root mean square error ranging between 1.4 to 4.6 days for physiological maturity, 5.4 to 9.3 kg ha⁻¹, 3.2 to 6.12 kg ha⁻¹, 0.8 to 3.3 kg ha⁻¹, and 2.2 to 4.2% for grain yield, biomass yield, straw yield and harvest index of the three durum wheat cultivars, respectively. These results are promising in making the best of crop simulation modelling in durum wheat production and the model has been successfully calibrated and evaluation for durum wheat in the central Ethiopia environment and compared to the results from the multi field experimentations.

Key words: Crop phenology; Genetic coefficients; Grain yield; Program run; Simulation.

5.1. INTRODUCTION

Durum wheat is one of the two dominant wheat species that was cultivating in Ethiopia (Abate and Walelign, 2023; Yewubdar *et al.*, 2023) and it was adapted different agro-ecological conditions in globally (Hussain *et al.*, 2022 and Negisho *et al.*, 2021). Bread and durum wheat were produced in Ethiopia by approximately 4.94 million households during 2022 cropping year under the meher and belg production systems (Alemayehu *et al.*, 2023). However, durum wheat production in Ethiopia reached 5.4 metric tons during the 2022 cropping year but it was remaining at a similar volume which was recorded during 2021 cropping season (DWPE, 2022).

The lack of adaptable varieties is the major problem for durum wheat production constraints under the variability of climate condition in Ethiopia (Lijalem *et al.*, 2021). Climate change is a problem on the global food and nutritional security through negative impact on the agricultural crop growth and productivity (Benitez *et al.*, 2023). Crop productivity fluctuates due to the changing climate and edaphic conditions (Kumar *et al.*, 2018; Raza *et al.*, 2019; Habib *et al.*, 2022; Lynch, 2022; Mwiti *et al.*, 2022). In Ethiopia, climate change is one of the major factors that influence agricultural productivity; particularly on the food security crops and it leads to food security problems in the country (Ahmed *et al.*, 2024). Production estimation methods like crop simulation for calculating production loss due to climate change required mitigate to solve effect of climate on crop production (Olabanji *et al.*, 2020; Mulla *et al.*, 2020).

Crop simulation models are quantitative tools based on scientific knowledge that can evaluate the effect of climatic, edaphic, hydrological and agronomic factors on crop growth and yield (Choudhury *et al.*, 2018; Kephe *et al.*, 2021). Crop models were used to quantitative descriptions of eco-physiological processes to predict plant growth, development and yield as influenced by soil, crop management and environmental conditions (Kant *et al.*, 2017; Kelly *et al.*, 2023). Prediction of productivity of any crop in a season through a crop simulation model has very important economic importance for a country (Jhonson *et al.*, 2022; Gavasso-Rita *et al.*, 2024). To improve crop productivity, the farmers must rapidly increase information about suitable management practices (Anantha *et al.*, 2021; Kumar *et al.*, 2024). However, the generation of new data through agronomic research methods is insufficient and time consuming to meet these needs. It is important for a country, where productivity of crops in any season may vary greatly depending on the prevailing weather conditions of that season (Mohammadi *et al.*, 2023). In

recent years, several dynamic crop growth simulation models have been developed to help in such a predictive process (You *et al.*, 2022; Eini *et al.*, 2023). The main role of a crop simulation model is to estimate crop production, resource use and environmental impact as a function of local weather (Feng *et al.*, 2023; Timlin *et al.*, 2024).

The Decision Support System for Agro-technology Transfer (DSSAT) is one of crop simulation models to simulate crop growth and development through computer programs (Mfwango *et al.*, 2018; Chen *et al.*, 2023) and decision support system for agronomic field experiment results under different soil and climate conditions (Desta, 2021). DSSAT enables users to determine which treatments are effective, stable, financially appealing, environmentally sound, or appropriate according to the users' objective (Singh *et al.*, 2020). More than forty crop growth models are included in DSSAT suit of models, and the CERES-Wheat program is the most popular (Hoogenboom *et al.*, 2019; Dar *et al.*, 2023)

DSSAT-CERES-Wheat program use, calibrated and validated of the program is needed in order for the large-area crop behaviour simulation and yield forecasting to precisely reflect the crops regional performance (Khatua *et al.*, 2023). Appropriate model calibration is essential for the effective usage of crop models and the cultivars genetic coefficient can be found by properly calibrating the model (Ma *et al.*, 2020). To calibrate the model, it needs crop-specific data, soil properties, agricultural management, and daily weather data (Ahmed *et al.*, 2017; Devkota *et al.*, 2022). Validation should be done by comparing simulated data with observed data and the dataset should be different from that used for calibration (Elgadi, 2019; Boote, 2020).

Endalew, (2019) and Girma, (2022) started calibrating and validating the DSSAT-CERES-wheat model in wheat in Ethiopia under a rain-fed growing environment. The current research was conducted to calibration and evaluation of DSSAT-CERES-wheat model for simulation of growth and yield of durum wheat cultivars under irrigated growing environment environment in central Ethiopia with the following objectives: i) to generate the genetic coefficient of the three durum wheat cultivars required for running of DSSAT model in Central Ethiopian condition and ii) to evaluation DSSAT crop model for simulation of growth and yield of durum wheat cultivars.

5.2. MATERIALS AND METHODS

5.2.1. Description of the Study Site

Please refer the description of the study area from subsection 1.11 (Page 32).

5.2.2. DSSAT Model

Decision Support System for Agro-technology Transfer (DSSAT-CERES-Wheat) v4.7.5 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, crop management files. Soil data 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 the site latitude and longitude. 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 weather file, soil file, A-file, and T-file, were created for running the model. The model was calibrated with set of field experimental data and subsequently validated with another dataset of field experiments. The genetic coefficients were obtained by using GLUE coefficients estimator method. GLUE is one of DSSAT programs used for estimating specific parameters of a variety. Seven characters of wheat were needed in the CERES-Wheat model in DSSAT (Table 5.1).

Table 5.1. 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)

5.2.3. Input Files for Model Calibration

5.2.3.1. Crop management data

The field experiments were carried out at Debre Zeit in central Ethiopia during the last five consecutive years (2018-2023). Three representative for lower, miduem and higher grain yielded durum wheat cultivars (*Alemtena*, *Bakalcha* and *Utuba*), which are selected from previous twenty tested cultivars which are conducted in experiment one (Chapter 2) used for chapter 5 experiment, with yield potential ranging from 4101.7 to 6025 kg ha⁻¹ (Table 2.11). The crops were grown under irrigated growing environment, which is no stress condition.

Table 5.2. Description of the cultivars

S/N	Cultivar	Year of release	Altitude (m above sea level)	Yield (kg ha ⁻¹)	Representative for	Maintaining centres
1	<i>Alemtena</i>	2016	1600–2200	4285	Medium yielded	DZARC
2	<i>Bakalcha</i>	2005	2000–2500	4101.7	Lower yielded	SARC
3	<i>Utuba</i>	2015	1800–2650	6025	Higher yielded	DZARC

Source: Table 2.11.

Seed rate used was 125 kg ha⁻¹. Unit plot size was 10 m length and 10 m width (20 m²). Yield and yield contributing related data were recorded. Harvested area was 8 m². 46 kg of P₂O₅ ha⁻¹ and 92 kg of N ha⁻¹ were applied. The first 2/3 of urea was applied at tiller initiation and the remaining 1/3 at the booting stage. The irrigation water was applied based on the FAO 56 report (Pereira, 2015) where wheat should be irrigated when 55% of the water at the depth of 1 m to 1.5 m is depleted. Water was applied using furrow irrigation and irrigation scheduling was set based on CROPWAT software V-8 and the gross irrigation water was 585.9 mm (Table 5.3). The

weeds were controlled by hand weeding. The stem and leaf rust diseases were controlled through Tilt 250 EC (Propiconazole) chemical application at the rate of 0.5 L per hectare.

5.2.3.2. Soil properties

These samples were 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 were presented in Tables 5.4, 5.5, and 5.6, which detail the physical properties, chemical characterization, and water holding capacity of the experimental soil, respectively.

Table 5.3. Irrigation water applied to the crop during 2020 and 2021 cropping seasons.

Irrigation frequency	Amount of water applied after planting (mm)
November 16	22.8
November 26	23
December 6	31
December 16	34
December 26	36
Janaury 5	47
Janaury 15	47.5
Janaury 25	49
February 4	56.9
February 14	56
February 24	49.7
March 6	49
March 16	48
March 25	36
Total	585.9

Source = Table 2.2.

Table 5.3. 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 5.4. 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 ₂ O)	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
NH ₄ ⁺ N (mg kg ⁻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.

Table 5.5. 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 wilting 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.

5.2.3.3. Weather data

The weather data such as maximum and minimum temperature (°C), daily rainfall (mm), and solar radiation (MJm²d⁻¹) for 5 years (2018-2023) were obtained from National Metrology station agency at DZARC climate and geospatial department. The raw data was compiled in MS Excel and converted to the format of the DSSAT to form the baseline dataset from observed climate data.

5.2.4. Observed Data Collection

Days to emergence was determined by counting the days from the date of planting to the date when 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 spade at 25 cm depth from the middle portion of each plot. Days to flowering was recorded by counting the number of days from the date of planting to the date when 90% of 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, reproductive part (spike) were separated and dried in an oven at 70° 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 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 threshing 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 kilogram per hectare.

5.2.5. Statistical Analysis for Model Calibration and Evaluation

Statistical analysis of the degree of coincidence between simulated and observed values were done by using of the statistical measures root-mean square error (RMSE) or percent of normalized root mean square error (NRMSE), index of agreement (d), and coefficient of determination (R²) (Nakagawa *et al.*, 2017; Li *et al.*, 2020). Normalized root-mean square error (NRMSE %) measured the relative difference of simulated over observed data (Endalew, 2019). These statistical measures are described as follows:

$$NRMSE(\%) = \left[\frac{RMSE}{\bar{O}} \right] * 100$$

where O_i and S_i denote observed and simulated values, respectively, \bar{O} and \bar{S} are the observed and simulated mean values, respectively, n is the number of data used.

5.2.6. 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 cultivars are required. These

coefficients are specific to each 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 2018–2019 and 2019–2020 cropping seasons 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 cultivars from the 2018–2019 and 2019–2020 cropping seasons at DZARC.

However, the three durum wheat cultivars were not included in the DSSAT genotype file, necessitating the start of the calibration process by determining the genetic coefficients of these cultivars. Initial genetic coefficient values were obtained from the model cultivars known as MARIS FUNDIN (cultivar from model), which are already available in DSSAT. The computed CSP values for the test cultivars 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.

5.2.7. 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 to the observed values from the experiments conducted in 2020–2021, 2021–2022, and 2022–2023. 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).

5.3. RESULT AND DISCUSSION

5.3.1. Model Calibration

The genetic coefficients of the durum wheat cultivars obtained using the GLUE program are shown in Table 5.7. These genetic coefficients were derived from the field trial data of the tested durum wheat cultivars for the years 2019–2020. The genetic coefficient P1V for the cultivars *Alemtena*, *Bakalcha*, and *Utuba* was 5, 12.5, and 10 days, respectively. These results indicate that the tested durum wheat cultivars grown in Ethiopia require vernalization, as these cultivars are of the winter wheat type (Bega). The results of the vernalization coefficient (P1V) showed that the cultivar *Bakalcha* required a longer day for vernalization compared to *Utuba* and *Alemtena*. The photoperiod coefficient (genetic coefficient P1D) for *Alemtena*, *Bakalcha*, and *Utuba* cultivars was 10, 100, and 20, respectively. The tested cultivars exhibited variation in the grain filling period coefficient, with the cultivar *Utuba* showing the highest value (380 degree days) for genetic coefficient P5, followed by *Alemtena* (300 degree days) and *Bakalcha* (250 degree days).

The genetic coefficient G1 for the cultivars *Alemtena*, *Bakalcha*, and *Utuba* was 15, 14, and 11 kernel numbers/m², respectively. Additionally, the genetic coefficient G2 for *Alemtena*, *Bakalcha*, and *Utuba* cultivars was 46, 56, and 79 mg, respectively. There was considerable variation among the tested durum wheat cultivars in PHINT and in the genetic coefficient G3. The highest PHINT (80 degree days) was observed in the *Utuba* cultivar, followed by *Alemtena* (50 degree days) and *Bakalcha* (45 degree days). Significant variations were also noted among the cultivars in G3; cultivar *Bakalcha* recorded the highest G3 (1.2 g), followed by *Utuba* (0.8 g) and *Alemtena* (0.5 g), respectively. A higher G3 value indicates heavier seed weight (see Table 5.6). 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 5.6. Genetic coefficient of the durum wheat cultivars

Coefficients	<i>Alemtena</i>	<i>Bakalcha</i>	<i>Utuba</i>
P1V (Days)	05	12.5	10
P1D (% reduction in rate 10h ⁻¹ drop in pp)	10	100	20
P5 (degree day)	300	250	380
G1 (kernel Number/m ²)	15	14	11
G2 (milligram)	46	56	79
G3 (g dwt)	0.5	1.2	0.8
PHINT (degree day)	50	45	80

5.3.2. Model Evaluation

The observed results of phenology and yield parameters for model evaluation were collected for the *Alemtena*, *Bakalcha*, and *Utuba* durum wheat cultivars during the 2020–2021, 2021–2022, and 2022–2023 cropping seasons. These results were used as input for the DSSAT simulation model. The validation indices indicated that the results obtained from the simulation were satisfactory for these phenological parameters. The close proximity between the simulation values calculated with the DSSAT 4.7.5 CERES Wheat sub-module and the observed phenological values is significant for the model's ability to accurately predict future results in various aspects of crop management, soil characteristics, and environmental conditions. In this context, the percent of root mean square error (RMSE (%)) and percent error differences (PE (%)) values between the observed and simulated parameters obtained from calibration are crucial, as they suggest the model's acceptability. For instance, a PE (%) value below 15% indicates that the simulation is acceptable, while NRMSE values of <10%, 10–20%, 20–30%, and >30% denote very good, good, medium, and poor simulations, respectively (Aydoğdu *et al.*, 2023).

In the current research, the values of percent of normalized root mean square error (NRMSE) were obtained for days to maturity, grain yield (kg/ha), biomass yield (kg/ha), straw yield (kg/ha), and harvest index (%) of durum wheat cultivars for the 2020–2023 cropping seasons, as listed in Table 5.8. The NRMSE values for tested parameters are lower than 10% which indicated the model evaluation results for those parameters had denote very good (Table 5.8) and it have a chances to use this model for farther simulation in durum wheat cultivars under central Ethiopian conditions.

Table 5.7. Indicators of goodness of fit for crop phenology and yield of three durum wheat cultivars for DSSAT–CERES–Wheat module under irrigated growing environment.

Cultivars	Parameters	Obs.	Sim.	PE (%)	R ²	NRMSE (%)	d
<i>Alemtena</i>	Days to maturity (days)	108	115	6.1	0.94	4.58	0.95
	Grain yield (kg/ha)	4557	5126	11.1	0.86	9.29	0.72
	Biomass yield (kg/ha)	11557	12327	6.2	0.82	6.12	0.81
	Straw yield (kg/ha)	7000	7326	4.4	0.85	3.30	0.79
	Harvest index (%)	39	41.3	5.6	0.88	4.20	0.78
<i>Bakalcha</i>	Days to maturity (days)	103	105	1.9	0.99	1.4	0.70
	Grain yield (kg/ha)	4051	4532	10.6	0.88	8.4	0.75
	Biomass yield (kg/ha)	8530	9019	5.4	0.97	4.2	0.78
	Straw yield (kg/ha)	4479	4488	0.2	0.99	0.14	0.76
	Harvest index (%)	47.5	50.3	5.6	0.82	4.1	0.73
<i>Utuba</i>	Days to maturity (days)	111	116	4.3	0.70	3.1	0.77
	Grain yield (kg/ha)	5905	6345	6.9	0.66	5.2	0.85
	Biomass yield (kg/ha)	11651	12154	4.1	0.75	3.2	0.79
	Straw yield (kg/ha)	5746	5809	1.1	0.85	0.8	0.84
	Harvest index (%)	50.7	52.3	3.1	0.84	2.2	0.83

Obs. = Observed, *Sim.* = Simulated, *PE* = Percent error differences, *R*² = coefficient of determination, *NRMSE* = normalized root-mean square error, and *d* = index of agreement.

Similarly, the percent error differences (PE (%)) between the simulated and observed values were obtained for days to maturity, grain yield (kg/ha), biomass yield (kg/ha), straw yield (kg/ha), and harvest index (%) of durum wheat cultivars (Table 5.8). The PE (%) values for those parameters ranged from 0.2 to 11.1 % which is lower than 15%. Thus, these results indicated that the PE (%) values obtained from model calibration were acceptable when compared to the PE (%) values reported by Choudhury *et al.* (2018). Therefore, the results of the current model calibration indicate that the simulations using the DSSAT–CERES–Wheat module under different crop management practices in the study area and in regions with similar soil and climatic conditions, based on the calibrated and documented genetic coefficients of cultivars, are acceptable.

On the other hand, the coefficient of determination (R²) is one of the statistical analyses used to assess the degree of fit between simulated and observed values in crop models (Dar *et al.*, 2023). The result of R² values for winter wheat ranged from 0.43 to 0.99 (Xia *et al.*, 2015; Wang *et al.*, 2024). In the current study, the simulated results of R² values observed from simulations across different durum wheat cultivars ranged from 0.66 to 0.99 (Table 5.8) and it is in the acceptable ranges. Therefore, these recorded R² values indicate that the current calibration of the DSSAT

model is acceptable based on the documented genetic coefficients for the *Alemtena*, *Bakalcha*, and *Utuba* durum wheat cultivars, and that it has a strong potential to predict yield and growth responses of these cultivars under various crop management activities in the study area.

Finally, the index of agreement (d) also serves as a statistical analysis for testing the correlation between simulated and observed values in crop models (Gameh *et al.*, 2020; Saldaña and Cotes, 2021). During the model calibration the index of agreement results for the *Alemtena*, *Bakalcha*, and *Utuba* cultivars for days to maturity, grain yield (kg/ha), biomass yield (kg/ha), straw yield (kg/ha), and harvest index (%) of durum wheat cultivars ranged from 0.7 to 0.95 (Table 5.8). Therefore, the current index of agreement values from the DSSAT wheat model calibration for the tested cultivars are acceptable, as stated by Choudhury *et al.* (2018) and Endalew (2019), which suggest an index of agreement range of 0.52–0.99. Consequently, these recorded index of agreement values indicate that the current calibration of the DSSAT model is acceptable based on the recorded genetic coefficients of the tested durum wheat cultivars and has significant potential to simulate yield and growth responses to various crop management activities in the study area and in regions with comparable agro-climatic conditions.

5.4. CONCLUSION

Model calibration and evaluation were identified as the initial steps in simulating models under various agronomic management scenarios. The study focused on the calibration and evaluation of the DSSAT model to assess its potential for simulating the growth and yield of three durum wheat cultivars at Debre Zeit in central Ethiopia. Results from the model evaluation demonstrated that DSSAT-CERES-Wheat accurately predicted both phenology and yield parameters of the durum wheat cultivars when compared to the observed data for these parameters. During the evaluation process, metrics such as the percentage of normalized root mean square error (NRMSE %), the coefficient of determination (R^2), the index of agreement (d), and the percentage error differences (PE %) between simulated and observed values for the tested parameters were all found to be within acceptable ranges, indicating satisfactory model calibration and evaluation under irrigated growing conditions.

Conversely, the study highlighted that the percentage error differences between simulated and observed values for grain yield (kg ha^{-1}) were larger in comparison to those for days to maturity, biomass yield (kg ha^{-1}), straw yield (kg ha^{-1}), and harvest index (%) of the durum wheat cultivars. Further improvements to the model were deemed necessary to enhance the simulation of growth and yield-related traits, including productive tillers per plant, seed size, and seed shape, thereby increasing the accuracy of predictions regarding crop development and growth for field management in wheat production across different agronomic scenarios.

To improve the outcomes of crop simulation models in similar research, it was recommended that data collection be prioritized based on model requirements from diverse locations and crop management practices. This approach was suggested to enable crop-climate simulation modeling to reduce costs associated with multiple field experiments, optimizing the balance between these two methodologies in future technology generation and promotion efforts, ultimately supporting informed decisions regarding agronomic outcomes in the context of climate change dynamics.

5.5. REFERENCE

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6. SIMULATION OF DURUM WHEAT (*Triticum Turgidum* L.) GROWTH AND YIELD AS INFLUENCED BY DIFFERENT NITROGEN RATES AND IRRIGATION INTERVAL IN CENTRAL ETHIOPIA.

ABSTRACT

The study aimed to apply the DSSAT v4.7.5 model to simulate wheat growth and yield as influenced by nitrogen rates and irrigation intervals in central Ethiopia. The model was calibrated using two years of field experiments conducted during the 2018/19 and 2019/20 cropping years at Debre Zeit Research Center (DZARC), Central Ethiopia, to capture the genetic coefficients of the tested cultivar. Similarly, the model was evaluated using three years of field experiments conducted during the 2020/21, 2021/22, and 2022/23 cropping seasons at DZARC, Central Ethiopia. The impacts of different nitrogen fertilizer rates (0 kg ha⁻¹, 46 kg ha⁻¹, 92 kg ha⁻¹, 138 kg ha⁻¹, and 184 kg ha⁻¹) and irrigation intervals (I₁: application of water every seven days, I₂: application of water every ten days, and I₃: application of water every thirteen days) on Utuba durum wheat cultivar growth and yield were simulated based on a one-year field experiment conducted during the 2022/23 cropping season at DZARC, Central Ethiopia. This was done to assess the accuracy of the model in predicting wheat yield under different nitrogen rates and irrigation interval management scenarios. The results of the model simulation showed a strong agreement between the simulated and observed wheat grain yields for the 2022/23 cropping season, with percent normalized root-mean square error (NRMSE %) values ranging from 0.25% to 10%, from 1.05% to 14%, and from 1.65% to 23.01% under the respective irrigation applications of every seven days, every ten days, and every thirteen days. Additionally, the error differences (ED) and indices of agreement (d-stat) further supported the model's performance. Overall, the simulated DSSAT model demonstrated good accuracy in simulating the growth and yield of Utuba durum wheat cultivar in central Ethiopia, highlighting its potential for studying the impacts of various management practices and climate change.

Key words: Grain yield, Model-performance, Model-simulation, Phenology, Scenarios.

6.1. INTRODUCTION

Agriculture in Ethiopia plays a pivotal role in the nation's economy, contributing 50% to the gross domestic product (GDP), generating 80% of the country's exports, and employing approximately 75% of the population (Zerssa *et al.*, 2021). Despite its significance, the sector faces numerous challenges that hinder food security and self-sufficiency. Among these challenges are suboptimal agronomic management practices, including ineffective soil nutrient management, weed control, and crop protection strategies. Furthermore, the country grapples with climate variability, particularly erratic rainfall, which exacerbates agricultural challenges (Urgessa, 2014; Gebissa, 2021).

Effective management of nitrogen and water is critical for crop production worldwide (Plett *et al.*, 2020). Nitrogen is an essential nutrient for plants; when applied inadequately, it leads to stunted growth and reduced crop yields in both irrigated and rainfed systems (Usman, 2020; Negash *et al.*, 2023). In Ethiopia, a staggering 93% of the nation's water resources are dedicated to agriculture, significantly higher than the global average of 70% (Water and Ethiopia Archive (WEA), 2020). For comparison, Egypt's agricultural sector consumes about 85% of its total water resources (Gameh *et al.*, 2020). This data reveals that Ethiopia's water usage for agriculture exceeds that of Egypt by 8%, highlighting the urgent need for improved water management practices to enhance agricultural productivity and ensure food security in the country.

In summary, while agriculture is a cornerstone of Ethiopia's economy, its potential is undermined by poor agronomic practices and significant environmental challenges. Addressing these shortcomings through targeted interventions in nutrient and water management is essential for achieving sustainable agricultural development and enhancing food security.

Wheat is one of the key staple foods globally, providing nourishment to approximately 2.5 billion people (Bentley *et al.*, 2022). In Ethiopia, wheat plays a critical role in food security and is primarily produced by smallholder farmers using a rainfed cultivation system (Abate and Walelign, 2023). However, this rainfed system has not sufficiently addressed the issues of food security and self-sufficiency in the country. Notably, there is a significant yield gap in wheat production under rainfed conditions, with reported gaps of 61%, 55%, and 46% compared to

yields observed in research stations, farmers' plots, and potential yields, respectively (Fisseha *et al.*, 2020).

In response to these challenges, the Ethiopian government has initiated an agenda to enhance wheat production through irrigated systems, aimed at improving food security and self-sufficiency. However, the current lack of suitable irrigation and agronomic technologies hampers the ability to achieve high and sustainable wheat yields. Furthermore, developing new agronomic and irrigation technologies through traditional field research is a lengthy process that can take several years. To expedite the resolution of these research gaps, there is a pressing need for innovative and accessible technologies, such as computer programs, that can streamline research activities and facilitate faster implementation of solutions. By leveraging technology, Ethiopia can work towards more effective wheat production strategies, ultimately enhancing food security and self-sufficiency in the country.

The Decision Support System for Agro-technology Transfer (DSSAT) is a widely used tool for simulating crop growth and yield under different environmental conditions worldwide (Liu *et al.*, 2017; 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; Endalew, 2019; Abu *et al.*, 2019; Silva *et al.*, 2021; Mekides *et al.*, 2022; Bizuwork *et al.*, 2024). However, the evaluation of the DSSAT model under irrigated growing conditions has not yet been conducted in the central part of Ethiopia, and this prevents recommendations for public use to compare model simulations with observed data from actual experimental yields. Following this, a more detailed analysis of crop performance can be conducted for different management strategies (soil, plant, irrigation, and fertilizer) and climate change scenarios to determine the most promising and least risky practices.

In this study, aimed to apply the DSSAT v4.7.5 model to simulate *Utuba* durum wheat cultivar growth and yield as influenced by nitrogen rates and irrigation intervals in central Ethiopia. By comparing model predictions to field data collected from experimental plots, sought to assess the model's performance in predicting wheat yield under various nitrogen rate and irrigation interval management scenarios.

6.2. MATERIALS AND METHODS

6.2.1. Description of the Study Site

Please refer the description of the study site from subsection 1.11 (Page 32).

6.2.1.1. Weather Data

The weather database utilized daily data on rainfall, minimum and maximum temperature, and solar radiation for the year 2022/23. 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 presented in table 1.2.

6.2.1.2. Soil properties

Please refer the soil properties on subsection 5.2.3.2. (Page 165)

6.2.2. Treatments and Experimental Design

The treatments consisted of one improved durum wheat cultivar (*Utuba*), 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 6.1. 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 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 indicated in Table 4.1 on Page 132. Weeds were controlled through hand weeding.

Table 6.1. The studied factors and their treatment combination.

Factor	Treatment	Symbolic
Irrigation frequency	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
Nitrogen fertilizer 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 ₁ N ₁ , I ₁ N ₂ , I ₁ N ₃ , I ₁ N ₄ and I ₁ N ₅), (I ₂ N ₁ , I ₂ N ₂ , I ₂ N ₃ , I ₂ N ₄ and I ₂ N ₅), (I ₃ N ₁ , I ₃ N ₂ , I ₃ N ₃ , I ₃ N ₄ and I ₃ N ₅)	

6.2.3. Model Simulation

The genetic coefficient of the *Utuba* durum wheat cultivar, determined using the GLUE program calibration and evaluation method from the DSSAT model and described in Table 5.7 (page 190).

6.2.4. Data Collection and Measurements

Days to physiological maturity, grain yield, biomass yield, and harvest index were referring on subsection 2.2.5 (Page 45) and the leaf area index please refer on subsection 5.2.4 (Page 186).

6.2.5. Statistical and Model Quality Analysis

The observed data were analyzed using the statistical package GenStat software version 19 (Gomez and Gomez, 1984). Mean values were evaluated by using of Least Significant Differences (LSD) at 0.05 level of probability. The degree of coincidence between simulated and observed values assessed by NRMSE (%), d, and R² (Nakagawa *et al.*, 2017; Li *et al.*, 2020). The NRMSE (%) measured the relative difference between simulated and observed data (Endalew, 2019). These statistical measures are described as follows:

$$NRMSE(\%) = \left[\frac{RMSE}{\bar{O}} \right] * 100$$

Where O_i and S_i denote observed and simulated values respectively, \bar{O} and \bar{S} are the observed and simulated mean values respectively, n is the number of data used.

6.3. RESULTS AND DISCUSSION

6.3.1. Effect of Nitrogen Rates and Irrigation Intervals on Phenology, Growth and Yield Parameters of Durum Wheat.

6.3.1.1. Phenology and growth parameters

Physiological maturity

The analysis of variance conducted in this study demonstrated that both nitrogen rate and irrigation interval significantly influenced the number of days to physiological maturity of durum wheat. Specifically, the main effects of nitrogen rate were found to be significant at a $P \leq 0.05$, while both irrigation interval and the interaction between nitrogen rate and irrigation interval were significant at $P \leq 0.01$ (Table 6.2).

The interaction between nitrogen rate and irrigation interval further complicated the results. The number of days to maturity ranged from 95 to 113 days depending on the treatment combinations (Table 6.3). Specifically, the most extended period to physiological maturity was observed with the highest nitrogen rate (184 kg N ha^{-1}) coupled with the narrow irrigation interval (I_1), while the shortest duration was noted with no nitrogen and higher irrigation interval (I_3). Notably, the combination of 184 kg N ha^{-1} and I_1 resulted in an increase of approximately 15.93% in maturity time compared to the control treatment.

In summary, the findings suggest that both higher nitrogen rates and more frequent irrigation significantly prolong the time to physiological maturity in durum wheat, a result that is consistent with previous research conducted by authors such as Islam *et al.* (2018) and Tesfaye (2023). The implications of these results highlight the critical role of nitrogen and irrigation management in optimizing durum wheat growth and influencing maturation timelines (Hills *et al.*, 2020; Wubshet, 2020; Effah *et al.*, 2022).

Table 6.2. Mean squares values of phenology and yield of the durum wheat influenced by nitrogen rates under different irrigation intervals in 2022/23 at DZARC.

Source of variation	DF	Days to maturity	Leaf area index (m m ⁻²)	Grain yield (t ha ⁻¹)	Biomass yield (t ha ⁻¹)	Harvest index (%)
Replication (R)	2	45.06	0.10	0.1	0.78	0.43
Irrigation (I)	2	244.5**	1.66**	53.0**	174.54**	1384.76**
Error (R*I)	4	20.86	0.10	0.16	1.18	1.06
Nitrogen (N)	4	183.7*	1.30**	32.1**	197.50**	2.6 ^{ns}
I*N	8	11.42**	0.17**	3.99**	13.84**	5.28*
Error (R*I*N)	24	83.68	0.15	0.17	1.13	3.12
Grand mean		102.93	3.05	3.35	8.67	38.6
LSD (5%)		14.49	0.67	0.74	2.22	2.85
CV _{R*I*N} (%)		8.89	12.85	12.46	12.29	4.85

ns, *and **, non-significant, significant and highly significant at $P > 0.05$, $P \leq 0.05$ and $P \leq 0.01$, respectively. DF= Degrees of freedom, LSD = List significant different and CV (%) = Percentage of coefficient of variation.

Leaf area index

The mean square value from the analysis of variance indicated that the main effects of nitrogen rates, irrigation intervals, and their interaction had a significant impact on the leaf area index of durum wheat at $P \leq 0.01$ (Table 6.7).

The interaction between nitrogen rate and irrigation intervals significantly impacts the leaf area index of durum wheat at $P \leq 0.01$. The mean performance of the leaf area index ranged from 2.5 m m⁻² to 3.8 m m⁻² (Table 6.3). The highest leaf area index was recorded at an application of 184 kg of N ha⁻¹ with I₁, while the smallest leaf area index was observed in the control treatment with I₃ (Table 6.3). Increasing nitrogen rates from 0 to 184 kg N ha⁻¹ raised the leaf area index across all irrigation treatments. However, the largest leaf area index was observed with the application of I₁, followed by I₂ and I₃, respectively, under the same nitrogen rate application. This could be due to the greater effect of nitrogen fertilizer on tiller production under conditions of higher soil moisture content. In this context, various authors have also demonstrated that the leaf area index is significantly affected by nitrogen rates and irrigation levels (Al-Molhem, 2016; Saeed *et al.*, 2017; Islam *et al.*, 2018; Luo *et al.*, 2021; Qazizadah *et al.*, 2022; Noor *et al.*, 2023).

Table 6.3. Mean performance of phenology, growth and yield of the durum wheat influenced by nitrogen rates under different irrigation intervals in 2022/23 at DZRC.

Treatment	Days to maturity	Leaf area index (m m ⁻²)	Grain yield (t ha ⁻¹)	Biomass yield (t ha ⁻¹)	Harvest index (%)
I ₁ N ₁	97 ^{bc}	2.7 ^{cd}	1.5 ^{e-g}	3.44 ^{gh}	43.6 ^a
I ₁ N ₂	104 ^{a-c}	2.9 ^{b-d}	2.4 ^d	6 ^{ef}	40.0 ^b
I ₁ N ₃	108 ^{a-c}	3.6 ^a	5.7 ^b	14.1 ^c	40.43 ^b
I ₁ N ₄	110 ^{ab}	3.7 ^a	7 ^a	17.5 ^a	40.0 ^b
I ₁ N ₅	113 ^a	3.8 ^a	6.8 ^a	17 ^{ab}	40.0 ^b
I ₂ N ₁	96 ^{bc}	2.6 ^d	1 ^{gh}	2.3 ^{hi}	43.5 ^a
I ₂ N ₂	103.5 ^{a-c}	2.7 ^{cd}	2.1 ^{de}	5.1 ^{fg}	41.2 ^{ab}
I ₂ N ₃	105 ^{a-c}	3.3 ^{a-c}	4.8 ^c	11 ^d	43.64 ^a
I ₂ N ₄	106 ^{a-c}	3.6 ^a	6.6 ^a	15.2 ^{bc}	43.42 ^a
I ₂ N ₅	109 ^{a-c}	3.5 ^{ab}	6.4 ^{ab}	14.7 ^c	43.54 ^a
I ₃ N ₁	95 ^c	2.5 ^d	0.3 ^h	1.2 ⁱ	25.0 ^c
I ₃ N ₂	97.5 ^{bc}	2.6 ^d	1 ^{gh}	3.7 ^{gh}	27.03 ^c
I ₃ N ₃	98 ^{bc}	2.7 ^{cd}	1.2 ^{fg}	4.8 ^{fg}	25.0 ^c
I ₃ N ₄	100 ^{a-c}	2.8 ^{cd}	1.9 ^{d-f}	7.6 ^e	25.0 ^c
I ₃ N ₅	102 ^{a-c}	2.8 ^{cd}	1.6 ^{e-g}	6.4 ^{ef}	25.0 ^c
Grand mean	102.93	12.85	3.35	8.67	38.6
CV (%)	8.89	3.05	12.46	12.29	4.85
LSD (5%)	14.49	0.67	0.74	2.23	2.85

Mean followed by the same letter are non-significant. LSD (%) = Listed significant different at 5% level, and CV (%) = Percentage of coefficient of variation, LS=level of significant.

6.3.1.2. Yield parameters

Grain yield

The statistical analysis of variance indicated that the grain yield of Utuba was significantly affected by the main effects of nitrogen rate, irrigation interval, and their interaction at $p \leq 0.01$ in 2022/23 cropping season (Table 6.2).

The results showed that the interaction between nitrogen rates and irrigation intervals significantly impacted grain yield at $p \leq 0.01$. The mean grain yield ranged from 0.3 to 7 t ha⁻¹ (Table 6.3). The highest yield was recorded with the application of 138 kg of N ha⁻¹ alongside I₁, whereas the smallest yield was registered under the control treatment with I₃ (Table 6.3). Increasing nitrogen rates from 0 to 138 kg N ha⁻¹ resulted in increased grain yield across all irrigation treatments (Table 6.3). However, the highest grain yield occurred with I₁, followed by I₂ and I₃ under the same nitrogen rates. This may be due to the greater soil moisture availability

at irrigation-1 during the grain-filling stage, which likely facilitated a more efficient mass flow of nitrogen from the soil to the root zone. In this context, various authors have also demonstrated that wheat grain yield is significantly influenced by nitrogen rates and irrigation levels (Khan *et al.*, 2023; Ra *et al.*, 2023; Shen *et al.*, 2023; Wang *et al.*, 2023; Dou *et al.*, 2024; Popal *et al.*, 2024; Yang *et al.*, 2024).

Biomass yield

The mean square from the analysis of variance indicated that the main effects of nitrogen rates, irrigation intervals, and their interaction significantly affected the biomass yield of durum wheat at $p \leq 0.01$ (Table 6.2).

The mean performance results indicated that the biomass yield of durum wheat under the interaction of nitrogen rates and irrigation intervals ranged from 1.2 t ha⁻¹ to 17.5 t ha⁻¹ (Table 6.3). The highest biomass yield per hectare was recorded with a nitrogen application of 138 kg N ha⁻¹ at I₁, while the smallest biomass yield per hectare was observed with null nitrogen rates at I₃ (Table 6.3). This research indicates that the biomass yield per hectare recorded with the application of 138 kg N ha⁻¹ at I₁ was the highest compared to the yields from other tested nitrogen rates at each irrigation interval. However, the biomass yield per hectare registered with 138 kg N ha⁻¹ at I₁ was not significantly different from the biomass yields recorded with 184 kg N ha⁻¹ at I₁ and 138 kg N ha⁻¹ and 184 kg N ha⁻¹ at I₂ (Table 6.3).

Increasing nitrogen rates from 0 to 138 kg ha⁻¹ significantly increased the biomass yield of durum wheat across all irrigation frequencies, whereas increasing nitrogen rates from 138 to 184 kg ha⁻¹ did not significantly boost biomass yield at any irrigation interval (Table 6.3). As a result, the application of 138 kg ha⁻¹ is deemed the optimum nitrogen rate for maximizing biomass production in durum wheat under irrigated production systems. Furthermore, previous research has indicated that nitrogen rate and irrigation levels influence the biomass yield of wheat (Si *et al.*, 2020; Gunawat *et al.*, 2023; Obour *et al.*, 2023; Schaller *et al.*, 2023; Burton *et al.*, 2024; Dass *et al.*, 2024).

Harvest index

The analysis of variance revealed that both the main effect of irrigation intervals and the interaction effect between nitrogen rate and irrigation interval significantly affected the harvest index of durum wheat at $p \leq 0.01$ and $p \leq 0.05$, respectively. However, the main effect of nitrogen rate did not significantly influence this parameter at $p \geq 0.05$ (Table 6.2).

The interaction mean performance of the harvest index ranged from 25.0% to 43.64% (Table 6.3). The highest harvest index was recorded with the application of 138 kg of N ha⁻¹ in conjunction with I₂, while the lowest harvest index was noted for the 0, 138, and 184 kg of N ha⁻¹ under I₃ (Table 6.3). Nonetheless, the highest harvest index was observed with the application of I₁, followed by I₂ and I₃ under the same nitrogen rate applications. This could be attributed to the presence of sufficient soil moisture content for grain yield production, which in turn led to an increased harvest index. Furthermore, various authors have shown that the harvest index of wheat is significantly affected by the interaction of nitrogen rates and irrigation regimes (Baloch *et al.*, 2014; Katohar *et al.*, 2023; Köse *et al.*, 2023; Zain *et al.*, 2023).

6.3.2. Simulation of Durum Wheat Phenology, Growth and Yield as Influenced by Nitrogen Rates and Irrigation Intervals.

The observed results of phenology and yield parameters for model analysis were collected from the *Utuba* durum wheat cultivar during the 2022/23 cropping year, under varying nitrogen rates and irrigation intervals. All treatment combinations (irrigation interval and nitrogen rates) were used as input in the DSSAT simulation model (Table 6.1). The close alignment between the simulation values calculated with the DSSAT 4.7.5 CERES Wheat sub-module and the observed phenology and yield parameter values is crucial, as it indicates the model's ability to accurately predict future outcomes in various aspects of crop management, soil characteristics, and environmental conditions, efficiently and cost-effectively.

In this context, accurate model simulation requires the following parameters: percent of error differences (PE (%)), percent of normalized root mean square error (NRMSE), coefficient of determination (R²), and index of agreement (d). For instance, if the PE (%) values are below 15%, the simulation is deemed acceptable. Similarly, NRMSE values of less than 10% are

categorized as very good, 10–20% as good, 20–30% as medium, and greater than 30% as poor (Choudhury *et al.*, 2018; Aydođdu *et al.*, 2023).

The simulation result is considered excellent when the NRMSE is very good (less than 10%), good (10–20%), fair (20–30%), and poor (greater than 30%) Jamieson *et al.* (1991). The coefficient of determination (R^2) is a statistical measure that indicates the degree of correlation between simulated and observed values in crop models (Dar *et al.*, 2023). In the DSSAT model, the acceptable R^2 values for winter wheat range from 0.43 to 0.99 (Xia *et al.*, 2015; Wang *et al.*, 2024). Likewise, the index of agreement (d) serves as another statistical method for assessing the agreement between simulated and observed values in crop models (Gameh *et al.*, 2020; Saldaña and Cotes, 2021).

6.3.2.1. Simulated phenology and growth parameters

Simulated physiological maturity

The interaction between nitrogen rates and irrigation interval significantly influenced the simulated physiological maturity of durum wheat, as summarized in Table 6.4. Notably, the simulation results indicated that the number of days to physiological maturity was consistently estimated to be 3 to 4 days longer than the observed values across all treatment combinations of nitrogen rates and irrigation intervals. This discrepancy suggests that the DSSAT-CERES-Wheat model tended to overestimate the duration to physiological maturity.

Among all interactions analyzed, the model revealed the highest simulated days to physiological maturity as compared to observed data. This finding underscores the effectiveness of the DSSAT-CERES-Wheat model in simulating the phenological development of durum wheat under varying management conditions. However, it is crucial to note that the model's predictive accuracy is evaluated through statistical metrics such as the coefficient of determination (R^2) and the model efficiency statistic (d). The current study demonstrated that the DSSAT-CERES-Wheat model provided an acceptable and reliable simulation of physiological maturity in response to different nitrogen rates and irrigation intervals, as detailed in Table 6.4.

Accurate simulation of physiologically mature stages is vital for reliable predictions of subsequent crop growth and yield outcomes. Relevant literature supports the model's applicability; previous studies by Elgadi (2019) and Endalew (2019) corroborated the capability of the DSSAT-CERES-Wheat model to predict physiological maturity under diverse agronomic practices and climatic conditions.

In summary, while the DSSAT-CERES-Wheat model demonstrates strong potential for simulating physiological maturity in durum wheat as influenced by nitrogen rate and irrigation interval, there remains a slight tendency to overestimate the duration to maturity, which might need addressing in future refinements of the model for improved accuracy.

Table 6.4. Indicators of goodness of fit for days to maturity of durum wheat for DSSAT–CERES–Wheat model evaluation as influenced by nitrogen rates and irrigation intervals during 2022/23 cropping season.

Parameter	Irrigation intervals	N-rates (kg ha ⁻¹)	Obs.	Sim.	ED	R ²	NRMSE %	d-stat
Days to maturity	Irrigation-1 (I ₁)	0	97	100	+ 3	0.76	3.05	0.72
		46	104	108	+ 4	0.71	3.77	0.68
		92	108	111	+ 3	0.84	2.74	0.75
		138	110	112	+ 2	0.95	1.80	0.82
		184	113	115	+ 0.2	0.96	1.75	0.84
	Irrigation-2 (I ₂)	0	96	100	+ 4	0.68	4.08	0.60
		46	103.5	105	+ 1.5	0.97	1.44	0.85
		92	105	107	+ 2	0.94	1.89	0.80
		138	106	110	+ 4	0.72	3.70	0.70
		184	109	111	+ 2	0.95	1.82	0.81
	Irrigation-3 (I ₃)	0	95	98	+ 3	0.75	3.11	0.71
		46	97.5	100	+ 2.5	0.89	2.53	0.77
		92	98	102	+ 4	0.70	4.00	0.65
		138	100	103	+ 3	0.82	2.96	0.73
		184	102	104	+ 2	0.90	1.94	0.79

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.

Simulated leaf area index

The simulated leaf area index (LAI) of durum wheat for all tested treatments was higher than the observed LAI in both irrigation intervals (Table 6.5). The maximum simulated and measured

LAI was compared at the booting stage for the interactions of nitrogen and irrigation treatments (I₁N₁, I₁N₂, I₁N₃, I₁N₄, I₁N₅; I₂N₁, I₂N₂, I₂N₃, I₂N₄, I₂N₅; and I₃N₁, I₃N₂, I₃N₃, I₃N₄, I₃N₅).

The LAI for both simulated and observed values at zero nitrogen fertilizer rates with I₃ (I₃N₁) was significantly lower than that of the other nitrogen and irrigation treatments (Table 6.5). Conversely, the highest LAI for both the simulated and observed values was recorded with an application of 184 kg N ha⁻¹ under I₁ (I₁N₅). Additionally, I₁ and the application of 184 kg N ha⁻¹ resulted in the maximum LAI. The quality of the model simulation is primarily determined by the values of PE (%) and NRMSE (%) (Table 6.5). Therefore, the DSSAT-CERES-wheat model currently demonstrates an acceptable simulation of LAI (Table 6.5) and is accurate for future predictions of LAI under different agronomic management practices. Furthermore, previous research has also indicated that the DSSAT-CERES-wheat model is essential for predicting accurate LAI results under varying agronomic, soil, and climatic conditions (Ji *et al.*, 2014; Wei *et al.*, 2022; Yang *et al.*, 2024).

Table 6.5. Indicators of goodness of fit for leaf area index of durum wheat for DSSAT–CERES–Wheat model evaluation as influenced by nitrogen rates and irrigation intervals during 2022/23 cropping season.

Parameter	Irrigation intervals	N-rates (kg ha ⁻¹)	Obs.	Sim.	ED	R ²	NRMSE %	d-stat
Leaf area index (m ² /m ²)	Irrigation-1 (I ₁)	0	2.7	2.9	+ 0.2	0.84	7.14	0.73
		46	2.9	3.1	+ 0.2	0.88	6.67	0.70
		92	3.6	3.7	+ 0.1	0.75	2.74	0.65
		138	3.7	3.8	+ 0.1	0.84	2.67	0.85
		184	3.8	4.2	+ 0.4	0.84	10.00	0.76
	Irrigation-2 (I ₂)	0	2.6	2.7	+ 0.1	0.85	3.77	0.78
		46	2.7	2.9	+ 0.2	0.82	7.14	0.68
		92	3.3	3.5	+ 0.2	0.85	5.88	0.78
		138	3.6	3.7	+ 0.1	0.82	2.74	0.73
		184	3.5	3.7	+ 0.2	0.84	5.56	0.76
	Irrigation-3 (I ₃)	0	2.5	2.6	+ 0.1	0.88	3.92	0.68
		46	2.6	2.7	+ 0.1	0.75	3.77	0.73
		92	2.7	2.9	+ 0.2	0.89	7.10	0.73
		138	2.8	3.1	+ 0.3	0.82	10.17	0.85
		184	2.8	3.0	+ 0.2	0.87	6.90	0.78

Obs.= Observed, *Sim.*= Simulated, *ED*=Error differences, *R*²=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.

6.3.2.2. Simulated yield parameters

Simulated grain yield

The current model simulated research results under the interaction effect of nitrogen rates and irrigation intervals, as presented in Table 6.6. The simulation indicated that the model successfully predicted good values of grain yield for all tested treatments.

The DSSAT model was utilized to simulate wheat yield for the nitrogen and irrigation treatments in the year 2022/23 (Table 6.6). The percent error differences (PE %) between the simulated and measured yields under I₁, I₂, and I₃ ranged from +0.95% to +2.81%, +1.35% to +2.7%, and +0.78% to +2.49%, respectively (Table 6.6). Generally, the positive percent errors indicate that the simulated yields are slightly higher than the measured yields. The model quality was assessed using the percent of normalized root-mean square error (NRMSE %).

The model-simulated values of NRMSE recorded for I₁, I₂, and I₃ under all tested nitrogen rates are suitable for predicting future grain yield production under various agronomic management practices and climate conditions. Choudhury *et al.* (2018) and Aydoğdu *et al.* (2023) reported that NRMSE values can be classified as very good (< 10%), good (10–20%), fair (20–30%), and poor (> 30%). The R² values for wheat ranged from 0.43 to 0.99 (Xia *et al.*, 2015; Wang *et al.*, 2024).

Therefore, the current simulated results presented in Table 6.6 indicate that the model simulation, influenced by nitrogen rates and irrigation frequency, is acceptable and has potential for predicting future model analyses under different agronomic management practices, soil types, and climate conditions in the study areas, as well as in areas with similar agro-climatic conditions. In this context, previous research has also indicated that the DSSAT-CERES-wheat model is one of the crop models capable of predicting wheat grain yield under the effects of nitrogen rates and irrigation frequency (Sen *et al.*, 2017; Araya *et al.*, 2019; Gameh *et al.*, 2020).

Table 6.6. Indicators of goodness of fit for yield of durum wheat for DSSAT–CERES–Wheat model evaluation influenced by nitrogen rates and irrigation intervals during 2022/23 cropping season.

Parameter	Irrigation Intervals	N-rates (kg ha ⁻¹)	Obs.	Sim.	ED	R ²	NRMSE (%)	d-stat
Grain yield (kg/ha)	Irrigation-1 (I ₁)	0	1500	1595	+ 95	0.76	6.14	0.70
		46	2400	2525	+ 125	0.80	5.08	0.75
		92	5700	5867	+ 167	0.89	2.89	0.81
		138	7000	7257	+ 257	0.84	3.61	0.78
		184	6800	7081	+ 281	0.82	4.04	0.76
	Irrigation-2 (I ₂)	0	1000	1158	+ 158	0.71	14.0	0.62
		46	2100	2235	+ 135	0.75	6.23	0.69
		92	4800	5071	+ 271	0.78	5.49	0.72
		138	6600	6832	+ 232	0.85	3.45	0.80
		184	6400	6546	+ 146	0.91	2.26	0.85
	Irrigation-3 (I ₃)	0	300	378	+ 78	0.65	23.01	0.55
		46	1000	1126	+ 126	0.72	11.85	0.65
		92	1200	1423	+ 223	0.67	17.00	0.58
		138	1900	2134	+ 234	0.73	11.60	0.66
		184	1600	1849	+ 249	0.70	14.44	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.

Simulated biomass yield

The variability in biomass yield between simulated and observed values, influenced by the interaction effects of nitrogen rate and irrigation intervals, is presented in Table 6.7. The simulated biomass yield ranged from 76 to 190 kg, 153 to 300 kg, and 78 to 615 kg under I₁, I₂, and I₃, respectively (Table 6.7). These values were higher than the observed values for all combinations of nitrogen rate and irrigation intervals. Consequently, the highest biomass yield was recorded in the simulated results compared to the observed results for any interaction effect of nitrogen rates and irrigation intervals (Table 6.7).

The maximum biomass yield was observed with the application of 184 kg N ha⁻¹ under I₁, while the minimum biomass yield was recorded with a zero nitrogen rate under I₃ for both simulated and measured values (Table 6.7). Thus, the applied DSSAT-CERES-Wheat model effectively simulated the biomass yield across all tested treatments.

In the current research, the DSSAT-CERES-Wheat model's simulation of biomass yield, as affected by irrigation intervals and nitrogen rates, is presented in Table 6.7. The model demonstrated acceptable accuracy in predicting biomass yield under different crop management activities. In this regard, previous research also indicated that the DSSAT-CERES-Wheat model could potentially be used to predict accurate biomass yield outcomes for crops under varying nitrogen treatments and irrigation frequencies (Sen *et al.*, 2017; Zain *et al.*, 2023).

Table 6.7. Indicators of goodness of fit for biomass yield of durum wheat for DSSAT–CERES model evaluation influenced by nitrogen rates and irrigation intervals during 2022/23 cropping season

Parameter	Irrigation Intervals	N-rates (kg ha ⁻¹)	Obs.	Sim.	ED	R ²	NRMSE (%)	d-stat
Biomass yield (kg/ha)	Irrigation-1 (I ₁)	0	3440	3516	+ 76	0.90	2.19	0.80
		46	6000	6158	+ 158	0.89	2.60	0.78
		92	14100	14201	+ 101	0.96	0.71	0.87
		138	17500	17690	+ 190	0.93	1.01	0.84
		184	17000	17185	+ 185	0.92	1.08	0.82
	Irrigation-2 (I ₂)	0	2300	2581	+ 281	0.69	11.51	0.70
		46	5100	5319	+ 219	0.78	4.20	0.69
		92	11000	11300	+ 300	0.85	2.69	0.76
		138	15200	15434	+ 234	0.91	1.53	0.80
		184	14700	14853	+ 153	0.92	1.04	0.81
	Irrigation-3 (I ₃)	0	1200	1402	+ 202	0.65	15.53	0.56
		46	3700	3916	+ 216	0.75	5.67	0.65
		92	4800	4880	+ 80	0.88	1.65	0.79
		138	7600	7897	+ 297	0.81	3.83	0.69
		184	6400	7015	+ 615	0.71	9.17	0.58

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.

Simulated harvest index

The harvest index of durum wheat is one of the parameters estimated by the model. The highest harvest index result was observed under the simulated model value when compared to the actual harvest index value, as shown in Table 6.9. The results presented in Table 6.9 indicate that the model simulation results, influenced by irrigation interval and nitrogen rate, were closely aligned with the observed results. This suggests that the DSSAT-CERES model has the potential to predict future harvest indices of wheat under various environmental and management scenarios.

Furthermore, previous evaluations of the model indicate that the DSSAT-CERES-wheat model is suitable for predicting the harvest index in response to nitrogen and irrigation factors (Hafiza *et al.*, 2022).

Table 6.8. Indicators of goodness of fit for harvest index of durum wheat for DSSAT–CERES–Wheat model evaluation by nitrogen rate and irrigation interval influenced during 2022/23 cropping season

Parameter	Irrigation frequency	Nitrogen rate (kg ha ⁻¹)						NRMSE	
			Obs.	Sim.	ED	R ²	(%)	d-stat	
Harvest index (%)	Irrigation-1 (I ₁)	0	43.6	45.4	+ 1.8	0.85	4.04	0.66	
		46	40.0	41.0	+ 1	0.82	2.47	0.73	
		92	40.43	41.3	+ 0.87	0.88	2.13	0.70	
		138	40.0	41.0	+ 0.1	0.85	0.25	0.78	
		184	40.0	41.2	+ 1.2	0.85	2.96	0.78	
	Irrigation-2 (I ₂)	0	43.5	44.9	+ 1.4	0.75	3.17	0.69	
		46	41.2	42.0	+ 0.8	0.75	1.92	0.75	
		92	43.64	44.9	+ 1.3	0.87	2.85	0.75	
		138	43.42	44.3	+ 0.9	0.89	2.01	0.68	
		184	43.54	44.0	+ 0.46	0.84	1.05	0.81	
	Irrigation-3 (I ₃)	0	25.0	27.0	+ 2	0.82	7.69	0.79	
		46	27.03	28.8	+ 1.2	0.88	6.34	0.76	
		92	25.0	29.2	+ 4	0.77	15.50	0.84	
		138	25.0	27.0	+ 2	0.79	7.69	0.75	
		184	25.0	26.0	+ 1	0.68	3.92	0.75	

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.

6.3.3. Model Simulation Quality

In the DSSAT model application experiment, the major indicators of model quality are represented by the percent of normalized root mean square error (NRMSE %), the index of agreement (d), and the coefficient of determination (R²) (Nakagawa *et al.*, 2017; Endalew, 2019; Li *et al.*, 2020). In this context, the current research findings indicate that the R² values for the measured and simulated data regarding days to maturity, leaf area index, grain yield, biomass yield, and harvest index ranged from 0.66 to 0.97 (Tables 6.4, 6.5, 6.6, 6.7, and 6.8).

The quality of the simulated results is also reflected in the percentages of normalized root mean square error (NRMSE %), percent error differences (PE %), and the index of agreement (d-stat). In the DSSAT model, the quality of simulated results for the tested parameters is considered

acceptable when the percent error difference (PE %) values are below 15%, the percent of normalized root mean square error (NRMSE %) values are less than 10% or range from 10–20% (Aydoğdu *et al.*, 2023), the coefficient of determination (R^2) values range between 0.43 and 0.99 (Xia *et al.*, 2015; Wang *et al.*, 2024), and the index of agreement (d) values range between 0.52 and 0.99 (Choudhury *et al.*, 2018; Endalew, 2019). Thus, the current simulation results presented in Tables 6.4, 6.5, 6.6, 6.7, and 6.8 are considered acceptable. Similarly, the overall percent error difference was positive (+), indicating that the DSSAT model's simulated values for the tested parameters were greater than the observed values for the same parameters. Consequently, the model simulation results for the tested parameters, influenced by nitrogen rates and irrigation frequency, demonstrate high quality and are deemed acceptable.

6.4. CONCLUSION

In this study, the DSSAT–CERES Wheat model was utilized to simulate the phenology, growth, and yield of durum wheat as influenced by nitrogen rates and irrigation intervals. The simulation results indicated that the normalized root-mean-square error (NRMSE) values between the simulated and observed grain yields under irrigation–1, irrigation–2, and irrigation–3 ranged from 2.89% to 6.14%, 2.26% to 14%, and 11.6% to 23.01%, respectively. Similarly, the NRMSE values for biomass yield under irrigation–1, irrigation–2, and irrigation–3 ranged from 0.71% to 2.6%, 1.04% to 11.51%, and 1.65% to 15.53%, respectively. In contrast, the coefficient of determination (R^2) and the index of agreement (d-stat) of the model for the tested parameters influenced by nitrogen rates and irrigation intervals ranged from 0.66 to 0.97 and from 0.65 to 0.95, respectively. Therefore, the NRMSE, R^2 , and d-stat values obtained from the current model application indicate that the DSSAT–CERES Wheat model is acceptable for simulating durum wheat under various nitrogen management strategies, different irrigation practices, and diverse agronomic conditions in central Ethiopia. However, for the successful use of the DSSAT model, accurate calibration and evaluation are crucial to achieving model performance that approaches 100% agreement, thereby enabling the effective application of the model for agricultural decision-making. Finally, model calibration and evaluation in Ethiopia are limited due to a lack of appropriate data for model application. Therefore, collecting field experimental data, climate data, and soil data relevant to model application is essential for utilizing the model effectively in any part of the country, including the study area.

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7. SUMMARY, CONCLUSION AND RECOMMENDATIONS

7.1. Summary

Durum wheat (*Triticum turgidum* L.) is one of the key crops for food security and industry in the country. However, farmers in the study areas cultivate durum wheat using a rain-fed production system, which has resulted in low productivity and insufficient progress in addressing food security issues. Recently, wheat production utilizing irrigation systems has emerged as a new practice in Ethiopia, particularly in the study areas. To enhance durum wheat production under irrigated conditions, several major production challenges have been identified in these areas. These challenges include the lack of improved production technologies, such as suitable cultivars for irrigated systems; inadequate information regarding the comparative advantages of different production systems; insufficient recommendations on nitrogen fertilizer rates and irrigation intervals; and a lack of awareness regarding crop modeling under various agronomic management practices for durum wheat production. Therefore, this study was conducted to address the following general and specific objectives.

The general objectives of the study were to: 1) improve the production, grain quality, and nitrogen use efficiency of durum wheat under irrigated and rain-fed production systems, and 2) calibrate, evaluate and apply the DSSAT-CERES-Wheat model for durum wheat production under irrigated growing conditions. The specific objectives were designed to: (i) select promising durum wheat cultivars for the irrigated production system; (ii) choose feasible durum wheat cultivars for rain-fed production systems; (iii) evaluate the comparative advantages of irrigated and rain-fed systems on durum wheat production and grain quality; (iv) improve the recommended nitrogen rates for better nutrient use efficiency, grain quality, and yield of durum wheat cultivars in rain-fed systems; (v) evaluate the effects of nitrogen rates and irrigation intervals on nutrient use efficiency, grain quality, and yield of durum wheat; (vi) develop appropriate genetic coefficients for running the DSSAT-CERES-Wheat model with selected durum wheat cultivars (*Alemtena*, *Bakalcha* and *Utuba*); and finally, (vii) simulate the DSSAT model to accurately predict of growth and yield of durum wheat yield under various nitrogen rates and irrigation interval management scenarios.

Based on these objectives, field experiments and laboratory data were collected from 2020 to 2023. The field experiments were conducted in 2020, 2021, 2022, and 2023. In 2020 and 2021, the performance of durum wheat cultivars under irrigated and rain-fed production systems was evaluated. In contrast, in 2022 and 2023, the effects of nitrogen rates on the yield, grain quality, and nitrogen use efficiency of durum wheat under irrigation intervals and rain-fed systems were assessed. The calibration and evaluation of the DSSAT model for durum wheat growth and yield under irrigated growing environment were conducted, followed by the application of the DSSAT model to simulate growth and yield of durum wheat as influenced by nitrogen rates and irrigation intervals at DZARC in the central part of Ethiopia.

The overall summary of the results from the experiments is as follows: The first experimental result on the evaluation of cultivars under irrigated and rain-fed production systems indicated that, in the rain-fed production system, out of twenty tested cultivars, only *Mangudo*, *Tesfaye*, *Utuba*, *Tate*, and *Hitosa* recorded the highest grain yield per hectare, while *Bakalcha*, *Toltu*, *Bullalla*, *Fetan*, *Ude*, and *Utuba* exhibited the highest grain protein content. In the irrigated production system, among the tested twenty durum wheat cultivars, only *Tesfaye*, *Mangudo*, *Utuba*, *Tate*, and *Hitosa* achieved the highest grain yield, whereas *Bakalcha*, *Toltu*, *Bullalla*, *Fetan*, *Obsa*, and *Utuba* displayed the highest protein content. Similarly, the comparative advantages between the two production systems were evaluated through pairwise T-test analysis. The pairwise T-test analysis revealed that the rain-fed production system increased grain protein content, gluten content, gluten index, and SDS-sedimentation, while it decreased the number of productive tillers per plant, the number of spikelets per spike, the number of kernels per spike, grain yield, biomass yield, thousand-kernel weight, and hectoliter weight of durum wheat cultivars compared to the irrigated production system. Thus, the irrigated production system enhanced plant height (8.5%), productive tillers per plant (45.6%), spikelets per spike (25.8%), kernels per spike (42.1%), grain yield (40.9%), biomass yield (36%), thousand-kernel weight (25%), and hectoliter weight (39%) of durum wheat compared to the rain-fed system.

The findings from the second experimental trial on nitrogen rates in durum wheat cultivation demonstrate a clear relationship between nitrogen application and various production and quality parameters. Increasing nitrogen rates from 0 to 138 kg N ha⁻¹ generally improved all measured outcomes, except for starch content, which decreased. The extremes in measured parameters

were found at 184 kg N ha⁻¹ (maximum) and 0 kg N ha⁻¹ (minimum). In a cost-benefit analysis, applying 92 kg N ha⁻¹ yielded the highest marginal rate of return for both tested durum wheat cultivars. Notably, the *Mangudo* cultivar outperformed the *Utuba* cultivar concerning profitability associated with nitrogen application.

The results of the third experimental study on the effects of nitrogen rates and irrigation frequency on the yield and grain quality of durum wheat indicated that all examined parameters were significantly influenced by nitrogen rates and irrigation frequencies, as well as their interactions. Applying 184 kg N ha⁻¹ at the I1 irrigation frequency resulted in a considerable increase in yield and yield-related parameters. However, this outcome did not differ significantly from the results obtained with 138 kg N ha⁻¹ at the I2 irrigation frequency. Concerning grain quality metrics, such as protein and gluten content, the highest values were achieved with an application of 184 kg N ha⁻¹ at the I3 irrigation frequency. Additionally, grain quality under the I3 frequency was significantly superior to that under I1, although similar results were observed between I3 and I2 at certain nitrogen rates. The economic analysis revealed that the maximum marginal rate of return (MRR) of 1563.91% was obtained from the plots treated with 138 kg N ha⁻¹ at a ten-day irrigation interval (I2).

The fourth experiment focused on the calibration and evaluation of the DSSAT-CERES-Wheat model for durum wheat cultivars under irrigated conditions. The results of the model evaluation indicated that the studied model could accurately predict both phenological development and yield parameters when compared to actual observational data. Furthermore, the study suggests that the model could be enhanced to simulate additional growth and yield-related traits, such as productive tillers per plant and seed size and shape, thereby increasing the reliability of crop development forecasts for effective wheat field management. However, the study also revealed that the percent error in the simulated grain yield (kg ha⁻¹) was greater than the percent error observed for other parameters like days to maturity, biomass yield (kg ha⁻¹), straw yield (kg/ha), and harvest index (%). This discrepancy likely arises from the quality of the observable data used for model calibration. To enhance the accuracy of crop simulation models in future studies, researchers should prioritize data collection that aligns with model requirements. This should encompass diverse locations and various crop management practices. By improving data quality and suitability, crop-climate simulation modeling can help reduce costs associated with extensive

field trials and optimize the interplay between experimental and modeled approaches. This integration will support informed agronomic decision-making, particularly in the context of ongoing climate change challenges.

The fifth experiment aimed to apply the DSSAT-CERES-Wheat model to simulate the growth and yield of durum wheat as influenced by nitrogen rates and irrigation frequencies. The findings revealed that the normalized root-mean-square error (NRMSE) for simulated versus measured yields varied across different irrigation treatments. Specifically, for irrigation treatment-1 (irrigation-1), the NRMSE ranged from 2.89% to 6.14%. For irrigation treatment-2 (irrigation-2), the NRMSE spanned from 2.26% to 14%, and for irrigation treatment-3 (irrigation-3), it ranged from 11.6% to 23.01%. Additionally, the biomass yield NRMSE values under these irrigation treatments were as follows: irrigation-1 showed a range from 0.71% to 2.6%, irrigation-2 exhibited values from 1.04% to 11.51%, and irrigation-3 ranged from 1.65% to 15.53%. The model's performance was further assessed using two statistical metrics: the coefficient of determination (R^2) and the index of agreement (d-stat). The R^2 values indicated a strong correlation for parameters affected by nitrogen rates and irrigation frequency, ranging from 0.66 to 0.97. Similarly, the d-stat values ranged from 0.65 to 0.95, suggesting good agreement between simulated and observed data. The low NRMSE percentages demonstrate the model's accuracy, while the low R^2 and d-stat values indicate a high degree of fit between the predictive simulations and actual measured outcomes.

7.2. Conclusion

In conclusion, the initial experimental findings on the assessment of cultivars in both irrigated and rain-fed production systems indicated that the irrigated method significantly improved various parameters of durum wheat. Specifically, there were increases in plant height, productive tillers per plant, spikelets per spike, kernels per spike, grain yield, biomass yield, thousand-kernel weight, and hectoliter weight compared to the rain-fed system. In the second experiment, increasing nitrogen rates from 0 to 138 kg N ha⁻¹ generally enhanced all measured grain quality, except for starch content, which declined. The highest and lowest values for the measured parameters occurred at 184 kg N ha⁻¹ and 0 kg N ha⁻¹, respectively. In this experiment the cost-benefit analysis revealed that applying 92 kg N ha⁻¹ yielded the highest marginal rate of return

for tested both durum wheat cultivars. However, the Mangudo cultivar showed greater profitability associated with nitrogen application compared to the Utuba cultivar. In the third experiment, nitrogen rates and irrigation intervals influenced the growth, yield, and grain quality of the Utuba durum wheat. Applying 184 kg N ha⁻¹ at the I₁ interval resulted in increased yield and related parameters, although it did not significantly differ from the 138 kg N ha⁻¹ at the I₂ interval. All grain quality parameters, except starch content, achieved their highest values with the application of 184 kg N ha⁻¹ at the I₃ interval. However, the grain quality observed under the I₃ interval was significantly better than that of the I₁ interval, but not significantly different from the I₂ interval at specific nitrogen rates. The economic analysis indicated that the maximum marginal rate of return (MRR) of 1563.91% was obtained from plots treated with 138 kg N ha⁻¹ at the I₂ interval. The fourth experiment involved calibrating and evaluating the DSSAT-CERES-Wheat model for durum wheat cultivars in irrigated conditions. Results from the model evaluation suggested it could accurately predict both phenological development and yield parameters when compared to actual observational data. The study found that the percent error in the simulated grain yield (kg ha⁻¹) was greater than the percent error observed for other parameters such as days to maturity, biomass yield (kg ha⁻¹), straw yield (kg ha⁻¹), and harvest index (%). The fifth experiment aimed to utilize the DSSAT-CERES-Wheat model to simulate the growth and yield of durum wheat influenced by nitrogen rates and irrigation frequencies. The model's performance was evaluated using two statistical metrics: normalized root-mean-square error (NRMSE), the coefficient of determination (R²), and the index of agreement (d-stat). The NRMSE and R² values indicated a strong correlation for parameters affected by nitrogen rates and irrigation frequency, ranging from 0.66 to 0.97. Similarly, the d-stat values ranged from 0.65 to 0.95, indicating good agreement between simulated and observed data. The low NRMSE percentages demonstrate the model's accuracy, while the low R² and d-stat values reflect a high degree of fit between the predictive simulations and actual measured outcomes.

7.3. Recommendations

The overall recommendations from the experiments are as follows: The first experimental results regarding the evaluation of cultivars under irrigated and rain-fed production systems indicate that *Utuba* is a recommendable cultivar for future use by farmers in the area, as well as by those residing in regions with agro-climatic conditions similar to those of the study area. This cultivar

has the potential to produce a higher grain yield with improved protein content under both irrigated and rain-fed production systems. Conversely, the pairwise T-test analysis revealed that the irrigated production system significantly increases durum wheat grain production compared to the rain-fed production system. Therefore, for the study area and other regions with similar soil and climate conditions, the recommended production system is irrigated rather than rain-fed. In the second experimental trial, the field research and cost-benefit analysis indicated that the application of 92 kg N ha⁻¹ resulted in the highest yield production compared to other nitrogen treatments. Similarly, the cultivar *Mangudo* exhibited a higher grain yield compared to the cultivar *Utuba*, in terms of profitability associated with nitrogen application. Therefore, for the study area and regions with similar agro-climatic conditions, the application of 92 kg N ha⁻¹ is recommended as the optimal nitrogen rate for durum wheat production.

The third experimental study examined the effects of nitrogen rate and irrigation frequency on the yield and grain quality of durum wheat. It showed that the application of 138 kg N ha⁻¹, along with irrigated water applied at ten-day intervals (I2 irrigation frequency), is advisable due to the economic advantages demonstrated when compared to other tested treatments. Thus, applying 138 kg N ha⁻¹ in conjunction with I2 irrigation frequency is the most economically feasible and recommendable option for durum wheat production in the study area and in regions with similar soil and agro-climatic conditions.

The fourth experiment focused on the calibration and evaluation of the DSSAT-CERES-Wheat model for growth and yield predictions of durum wheat cultivars in irrigated environments. The recommended genetic coefficients derived from model calibration for the tested cultivars are as follows: *Alemtena* (P1V=05, P1D=10, P5=300, G1=15, G2=46, G3=0.5, PHINT=50), *Bakalcha* (P1V=12.5, P1D=100, P5=250, G1=14, G2=56, G3=1.2, PHINT=45), and *Utuba* (P1V=10, P1D=20, P5=380, G1=11, G2=79, G3=0.8, PHINT=80). Therefore, in the study area and in regions with similar agro-climatic and soil conditions, these recommended genetic coefficients can be utilized to simulate the growth and yield of durum wheat under various agronomic management scenarios.

The fifth experiment involved applying the DSSAT-CERES-Wheat model to simulate the growth and yield of durum wheat under varying nitrogen rates and irrigation frequencies. The

findings recommend that the DSSAT-CERES-Wheat model is a reliable tool for simulating various agronomic practices in durum wheat cultivation, particularly within the climatic context of central Ethiopia. Thus, the model can effectively assist researchers and farmers in optimizing growth and yield under different nitrogen and irrigation scenarios.

Overall, to address the agronomic management challenges posed by dynamic climate change for durum wheat production, crop model-based research is essential and will provide solutions to various crop production problems throughout the year.

8. APPENDICES

TABLES

Table 2.1. Monthly irrigation water applied to the crop calculated through CROPWAT model analysis (FAO, 2015)

Date	Day	Stage	Rain (mm)	Ks fract.	Eta (%)	Depl (%)	Net Irr (mm)	Deficit (mm)	Loss (mm)	Gr. Irr (mm)	Flow (l/s/ha)
16-Nov	1	Init	0	1	100	57	30.7	0	0	45.8	5.31
16-Dec	31	Dev	0	1	100	57	70.7	0	0	101	0.39
10-Jan	56	Mid	0	1	100	55	99.8	0	0	142.5	0.66
05-Feb	82	Mid	0	1	100	57	102.9	0	0	147	0.65
02-Mar	107	End	0	1	100	58	104.4	0	0	149.1	0.69
25-Mar	End	End	0	1	0	17	0	0	0	0	0

Rain = Rainfall in millimeter, Ks fract = Coefficients, Eta (%) = Percent of actual evapotranspiration, Depl (%) = Percent of depletion fraction, Net Irr (mm) = Net irrigation in millimeter, and Gr. Irr (mm) = Gross irrigation in millimeter. Source = soil and weather data from Debre Zeit Research Center, and all other required data form FAO 56.

FIGURES

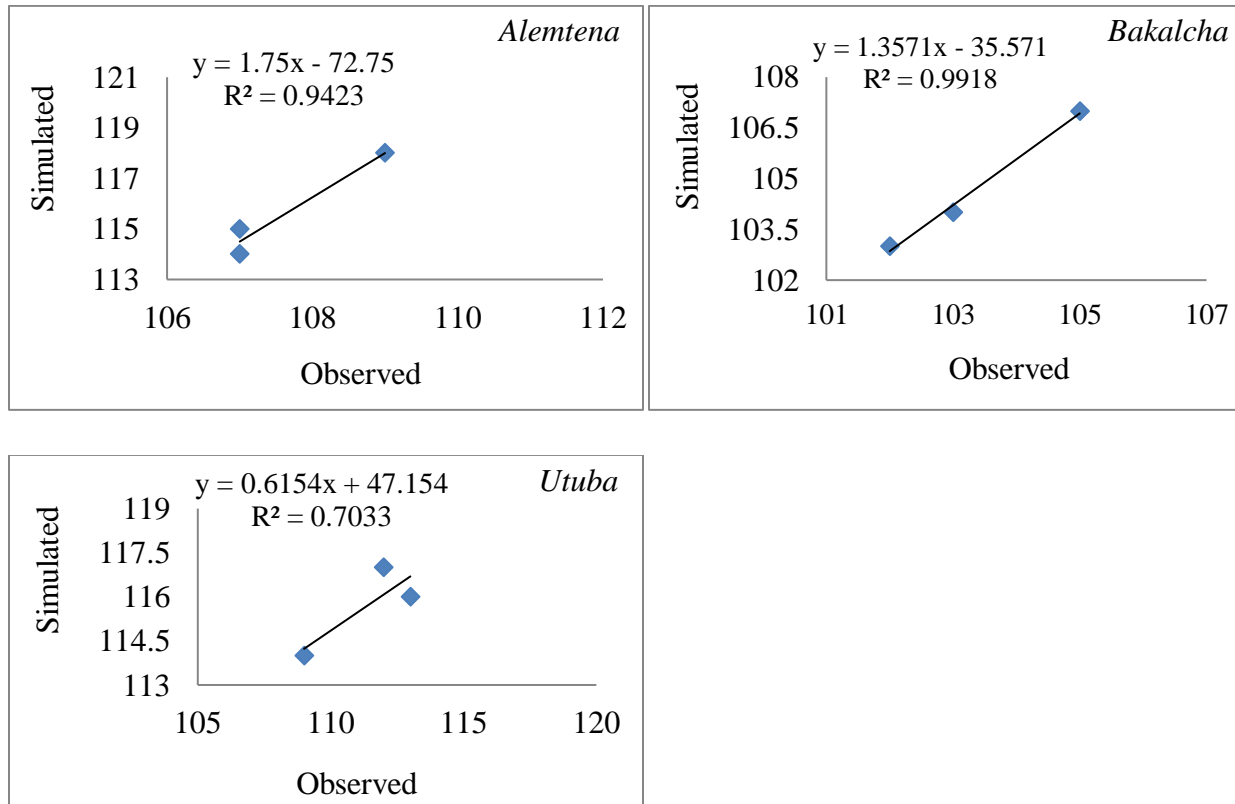


Figure 5.1. Relationship between observed and simulated values of days to physiological maturity in calibration for *Alemtena*, *Bakalcha* and *Utuba* cultivars of durum wheat.

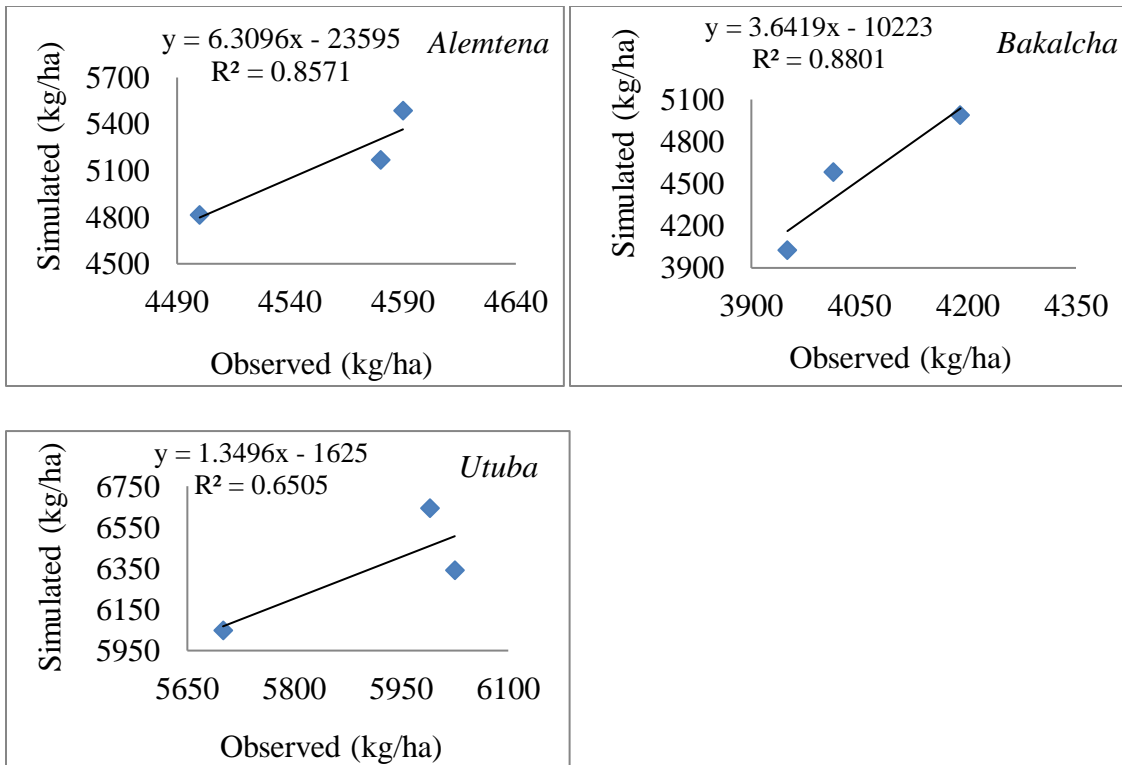


Figure 5.2. Relationship between observed and simulated value of grain yield in calibration for *Alemtena*, *Bakalcha* and *Utuba* cultivars of durum wheat.

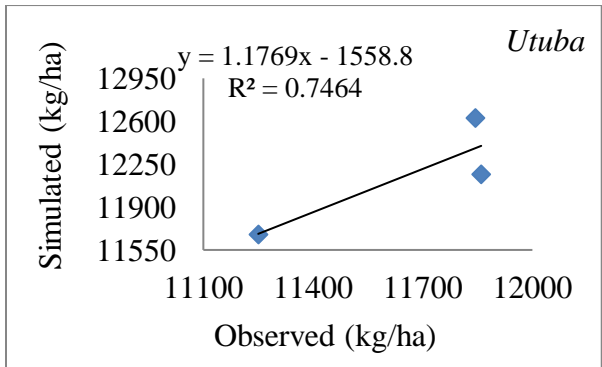
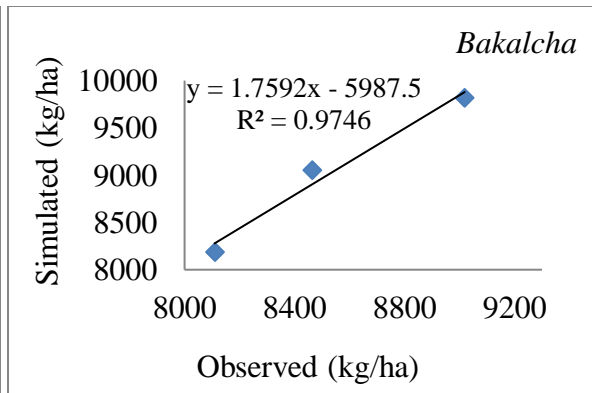
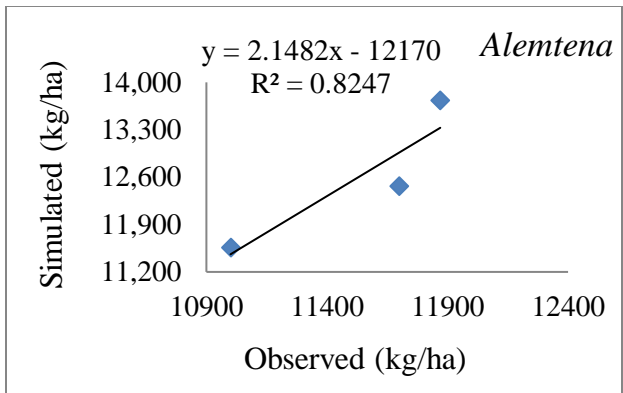
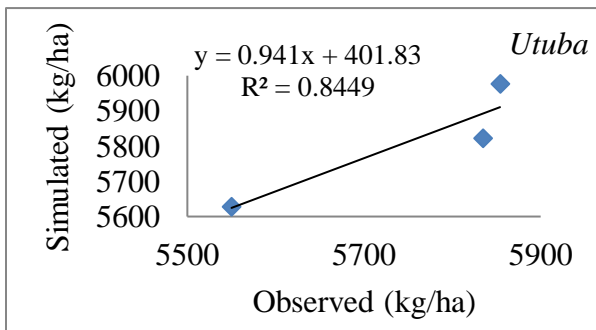
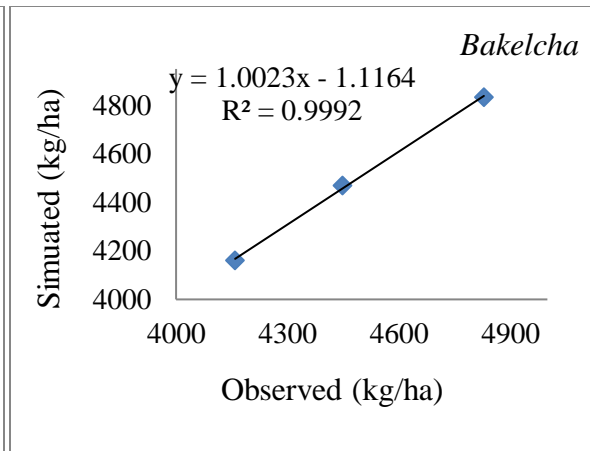
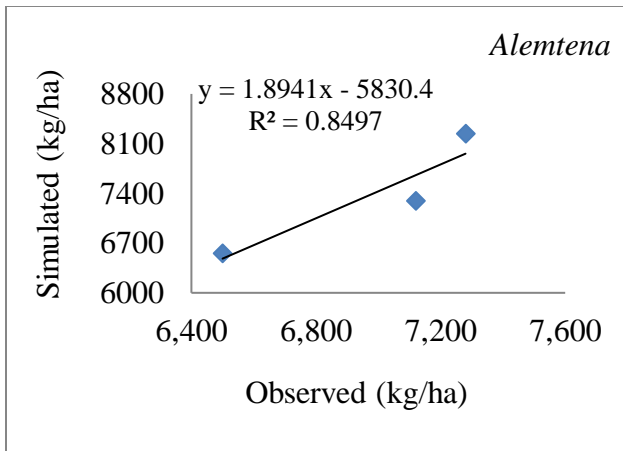
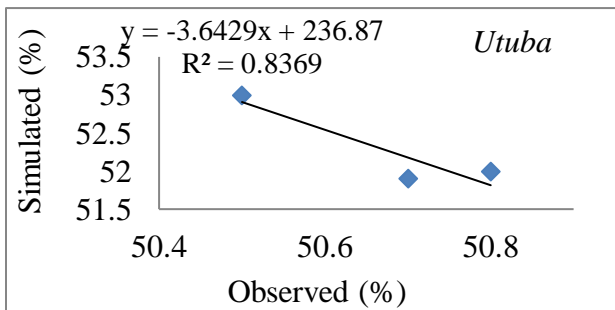
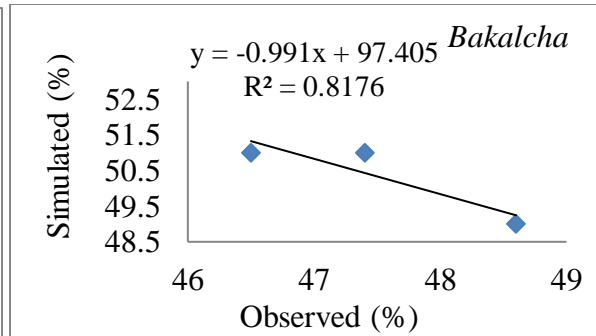
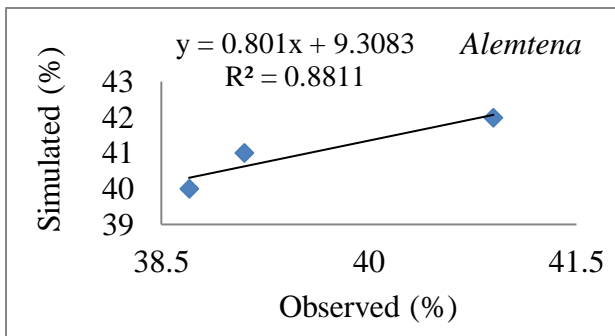


Figure 5.3. Relationship between observed and simulated value of biomass yield in calibration for *Alemtena*, *Bakalcha* and *Utuba* durum wheat cultivars.



5.4. Relationship between observed and simulated value of straw yield in calibration for *Alemtena*, *Bakelcha* and *Utuba* durum wheat cultivars.



5.5. Relationship between observed and simulated value of harvest index in calibration for *Alemnena*, *Bakalcha* and *Utuba* cultivars of durum wheat.