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Research Article

Growth, yield and grain quality responses of Durum Wheat (*Triticum turgidum* var. *durum*) cultivars to irrigated and rain-fed production systems at Debre Zeit, central Ethiopia

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Abstract: *Wheat production under the irrigation production system is a recent event in Ethiopia. There is limited information on the comparative advantage of the irrigated over rain-fed production systems on yield and grain quality of wheat. Thus, these researches were conducted to evaluate the performance of durum wheat cultivars under irrigation and rain-fed production systems. The treatments consisted of twenty durum wheat cultivars. The experiments were conducted in 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. After the variance homogeneity test combined analysis over the production years within the production systems was conducted. The effects of production systems on the tested parameters were evaluated by pair-wise T-test analysis. The combined results over 2020 and 2021 years indicated that the tested cultivars significantly affected the growth, grain yield and quality of durum wheat in each of the production systems. In each production system combined over the production years, the cultivars Mangudo, Tesfaye, Utuba, Tate, and Hitosa recorded the highest grain yield while the cultivars Bakalcha, Toltu, Bullalla, Fetan, and Utuba registered the higher grain protein content. The cultivar Utuba combined over 2020 and 2021 years recorded the highest grain yield with greater grain protein content in the rain-fed as well as in the irrigated production systems. According to the results of the pair-wise T-test analysis, the irrigated production system increased the plant height (8.5%), productive tillers per plant (45.6%), spikelet per spike (25.8%), kernel 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 irrigation production system was superior in most of the parameters of durum wheat compared to the rain-fed. Mangudo, Tesfaye, Utuba, Tate, and Hitosa could be promising cultivars for rain-fed as well as for irrigated systems for enhancing the grain yield of durum wheat in the study area and areas with similar agro-ecological conditions.*

Keywords: Durum Wheat, Grain yield, Hectoliter weight, Production system, Protein content
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1. Introduction

Durum wheat (*Triticum turgidum* var. *durum*) 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 (Abayisenga, 2015; De Vita, and Taranto, 2019). In Ethiopia, durum wheat is 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 1800 and 2800 m above sea level and rainfall distribution varying from 600 to 1200 mm per annum (Zemede, 2019; Kamil, 2020). Of the total wheat production areas in the world, durum wheat accounts for only 8%. About 75% of it is cultivated in the Mediterranean regions (Tidiane *et al.*, 2019; Ceglar *et al.*, 2021). In Ethiopia, both durum and bread wheat are cultivated in rain-fed production systems and form the total wheat cultivated areas of 1,605,654 only 561,979 hectares of land is covered by durum wheat (Tadesse *et al.*, 2022).

The productivity of durum wheat in Ethiopia is less than 2.2 to^{-1} (Temtme *et al.*, 2018) while its productivity in the studied area ranges between 2.92 t ha^{-1} and 3.85 t ha^{-1} (Mekuriaw and Ahmed, 2022). The small and large-scale farmers in Ethiopia are focused on bread wheat production compared to durum wheat production (Biggeri *et al.*, 2018). Therefore, the government of Ethiopia is importing durum wheat, which covers around 50 to 80% of the total wheat imports (Gurmu, 2017, 2017). On the other hand, more than 3.8 to 6 million hectares of land in Ethiopia is suitable for irrigation (Worqlul *et al.*, 2017). Especially, the lowland areas of the country are suitable for crop production under irrigation (World Bank, 2006). According to Makombe *et al.* (2007), irrigation development is a key for sustainable and reliable agricultural development leading to the overall development of Ethiopia. In this regard, the Ethiopian Government is heavily expanding irrigated wheat production throughout the country with the aim of minimizing the imbalance between supply and demand for wheat (Muchie, 2022).

About forty-two improved durum wheat cultivars were developed by the national research system in Ethiopia. These varieties are released exclusively for rain-fed production systems for different locations in the country. Expansion of durum wheat through the irrigation production system however requires the evaluation of these cultivars under this production system and in the rain-fed production system as well. Thus, this research was conducted with the aim of evaluating the performance of durum wheat cultivars under the irrigated as well as rain-fed production system.

2. Materials and Methods

2.1. Description of the study area

The experiments were conducted in 2020 and 2021 during the main rainy season (rain-fed) as well as in the off-season (irrigated) at Debre Zeit Agricultural Research Center (DZARC), Ada'a District of Oromiya Regional State, Ethiopia. Debre Zeit Agricultural Research Center is located at 8^{o}41′36″ latitude and 39^{o}03′17″ longitude at an altitude of 1880 m above sea level (Zemede *et al.*, 2019). The experimental site is located in the Central Highlands of the country and is suitable for the production of durum wheat. The weather data of the experimental site is presented in Figure 1 (Debre Zeit Agricultural Research Center Meteorological Station (2022). The average relative humidity of the area is 61.3% (NMSA, 2011) while the average rainfall during the experimental years was 796 mm. Moreover, the average minimum and maximum temperatures of the study area were 7.9 and 26.2 ^{0}C (Figure 1). The soil of the experimental site is heavy black soil, which contains a high amount of clay (52%) and medium amounts of silt (24%) and sand (18%). The soil pH is 6.61 with an organic matter content of 2.7%. The soil contains a very low amount of total nitrogen (0.58%) and an available P was 23.6 ppm (Table 1).

Table 1: Selected soil properties of the study site

Soil properties	Optimum values	Methods of soil analysis	Rating
pH (H_2O) 1: 2.5	6.27	pH meter(H_2O 1: 2.5)	Moderately acidic (Agegnehu *et al.*, 2021)
Available P (ppm)	23.6	Olson's sodium method	Otabbong *et al.*, 2009
Total N (%)	1	Kjeldahl method	Very low, (Kirk, 1950)
Organic carbon (%)	0.10	Walkley-Black method	Very low (De Vos *et al.*, 2007)
CEC (cmol(+)·kg^{-1})	51.59	ICP- Method (Hendershot and Duquette, 1986)	High (Virmani *et al.*, 1982)

pH = potential of hydrogen; P = phosphorus; N = nitrogen; CEC = Cation-exchange capacity; ICP = Inductively coupled plasma

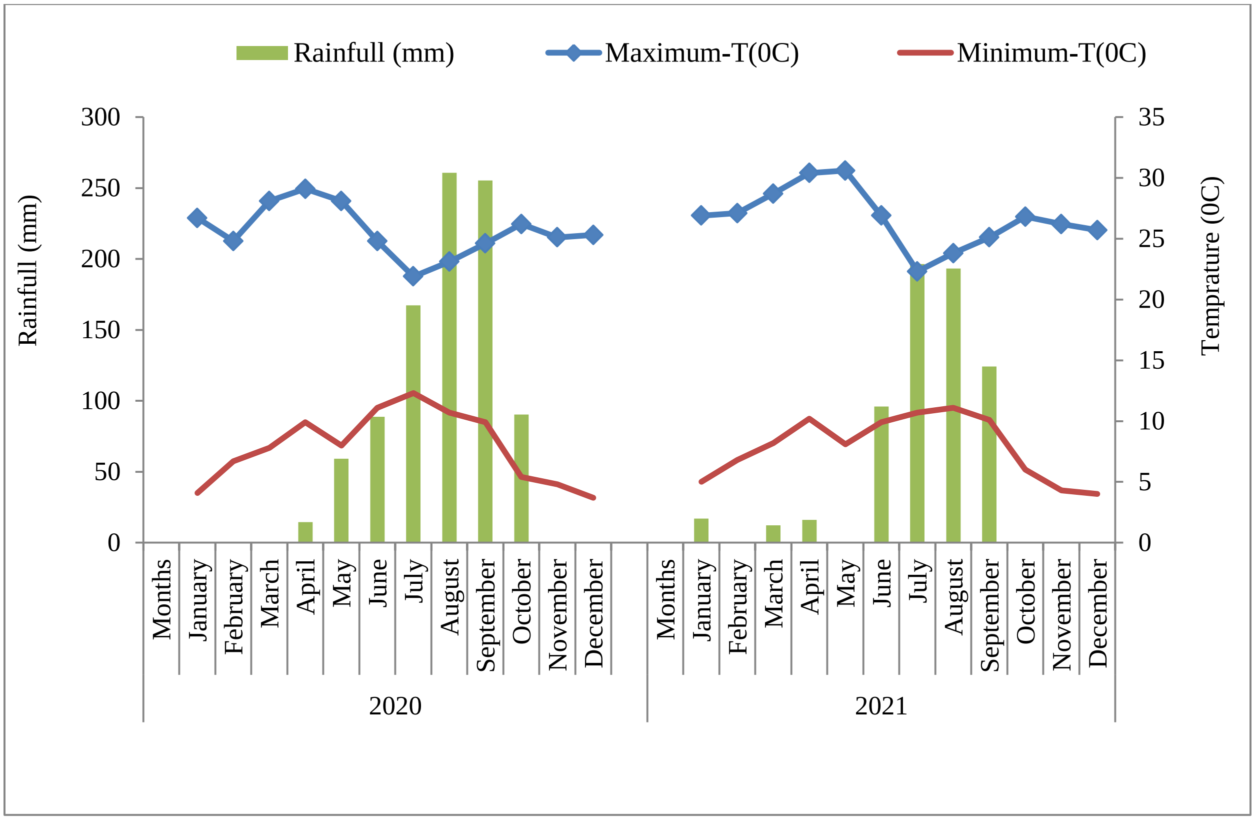

Figure 1: Rainfall and temperature distribution of the experimental site during the 2020 and 2021 cropping seasons

2.2. Experimental materials

Twenty improved durum wheat cultivars were evaluated under rain-fed and irrigated production systems in separate research experiments at Debre Zeit Agricultural Research Center, which were selected based on their grain yield and good grain qualities. The planting materials were released from 2002 to 2017 by Deber Zeit Agricultural Research Center (DZARC) and Sinana Agricultural Research Center (SARC).The grain yield production potential of the cultivars ranges between 2780 and 7630 kg ha^{-1}. The list and description of the cultivars are presented in Table 2.

Table 2: 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	*Alemtena*	2016	1600–2200	3000–5000	DZARC
2	*Bakalcha*	2005	2000–2500	3200–6700	SARC
3	*Bullalla*	2017	2000–2500	3950–7630	SARC
4	*Denbi*	2009	1800–2800	4000–5600	DZARC
5	*Dire*	2012	2000–2500	4900–5200	SARC
6	*Donmateo*	2017	1800–2650	4000–5500	DZARC
7	*Ejersa*	2005	2000–2500	3200–6200	SARC
8	*Fetan*	2017	1600–2200	3000–5000	SARC
9	*Gerardo*	1976	1800–2500	2000–3000	DZARC
10	*Hitosa*	2009	1800–2650	4000–6000	DZARC
11	*Mangudo*	2012	1800–2650	3500–6000	SARC
12	*Mokiye*	2012	450–1200	3500–5600	DZARC
13	*Obsa*	2006	2000–2500	4000–6000	SARC
14	*Tate*	2009	2000–2500	4200–5900	SARC
15	*Tesfaye*	2017	1800–2800	5000–5500	DZARC
16	*Toltu*	2010	2000–2500	4400–6000	SARC
17	*Ude*	2002	1800–2650	3000–5500	DZARC
18	*Utuba*	2015	1800–2650	4000–6500	DZARC
19	*Werer*	2009	450–1200	4000–4500	DZARC
20	*Yerer*	2002	1800–2650	3000–5000	DZARC

DZARC = Debre Zeit Agricultural Research Center, SARC = Sinana Agricultural Research Center

Source: Mekibib *et al*. (2020)

2.3. Treatments and experimental design

The treatments consisted of twenty durum wheat cultivars (Table 2), which were laid out in Randomized Complete Block Design. On the other hand the quality parameters of durum wheat were evaluated under laboratory conditions, where Completely Randomized Design was used. The experiments were conducted during the 2020, and 2021 main cropping seasons and during the 2020/21, and 2021/22 irrigation seasons. In the rain-fed experiment, the size of the plot was 3 m in length and 2 m in width (6 m^2) while in the irrigated production system the plot size was 5 m in length and 4 m in width (20 m^2). The spacing between plots and blocks in the rain-fed experiment was 0.5 m and 1 m while it was 1.5 m and 2.5 m in the irrigated experiment, respectively. Each cultivar was assigned to each plot randomly in both production systems.

2.4. Experimental procedures

In the rain-fed and irrigated production systems, the experimental lands were ploughed by a tractor and plots were prepared manually. The seeds of the improved durum wheat cultivars were planted at the rate of 125 kg per hectare by hand drill at a depth of 10 cm and then covered with soil under the rain-fed and irrigated production systems. Under the rain-fed production system, the seeds were sown on July 20, 2020, and July 18, 2021, while for irrigated conditions seeds were sown on November 16, 2020, and November 16, 2021.

In the rain-fed and irrigated production systems, all the recommended blended NPS fertilizer (100 kg ha^{-1}) was applied by banding the granules at the time of sowing while the urea fertilizer (200 kg of urea ha^{-1}) was applied in two splits. The first 2/3 of urea was applied at tiller initiation and the remaining 1/3 at the booting stage. Under the irrigated production system, 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 585.4 mm (Table 3).

The weeds were controlled by hand weeding in both production systems. In the rain-fed experiment, the stem and leaf rust diseases were controlled through Tilt 250 EC (Propiconazole) chemical application at the rate of 0.5 L per hectare. No diseases and insects' were observed during the irrigated production system. Harvesting was done manually in both production systems.

Table 3: Applied irrigation water calculated through CROPWAT model analysis (FAO, 2015)

Date	Day	Stage	RF (mm)	Ks	Eta (%)	DF (%)	NI (mm)	Deficit (mm)	Loss (mm)	GI (mm)	Flow (l/s/ha)
16-Nov	1	Initial	0	1	100	57	30.7	0	0	45.8	5.31
16-Dec	31	Developmental	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

RF = Rainfall; Ks = Crop coefficients, Eta (%) = Percent of a*ctual evapo-transpiration; DF = Percent of depletion fraction; NI = Net irrigation; GI = Gross irrigation*

Source: Pereir *et al*. (2015)

2.5. Data collection

Days to emergence were collected by counting the days from the date of planting to the date when 50% land was covered by the plants. Days to flowering were recorded by counting the number of days from the date of planting to the date when 90% of the head (spike) was flowered. The number of productive tillers per plant was counted from the plants grown at 0.1 m^2 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 was collected 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 weighed in kilograms and expressed in kilograms per hectare. Grain yield was obtained by trashing plants grown at a length of 1.5 m and a width of 0.6 m (0.9 m^2) of the net plot area. The grains were weighed in kilogram using a sensitive balance and expressed in kilogram per hectare. The thousand Kernel weight of durum wheat was recorded by weighing 1000 seeds by an electric seed counter using a sensitive balance. The weight was expressed in gram by adjusting it to a 12.50% moisture level. The hectoliter weight was also recorded as the weight of grains of the seed burohectoliter mass device using an electronic balance. The weight was then converted into kilogram per hectoliter *at* 12.50% moisture level. The protein content (%) was determined based on the nitrogen content of the grain determined using the micro-Kjeldehal method (Jung *et al.*, 2003) and the 5.75 conversion factors. Urea was used as a control.

2.6. Data analysis

The collected data were subjected to the ANOVA as described by Gomez and Gomez (1984). After Bartlett's homogeneity test, combined ANOVA over years within the production system was conducted using Gen-Stat-statistical software version 19. Cultivar was considered a fixed effect, whereas production years and replications were considered as a random effect. The effect of production systems on durum wheat was evaluated through pair-wise T-test analysis as indicated by Soriano *et al.* (2016). Whenever the ANOVA result of the variables showed significance ($P \leq 0.05$), mean separation between the treatments was performed using Duncan's multiple range test (DMRT) at $p < 0.05$ level of significance.

3. Results and Discussion

3.1. Phenological and vegetative growth responses of durum wheat cultivars to irrigated and rain-fed production systems

3.1.1. Days to emergence

The combined analysis of variance over the years showed that cultivar influenced ($p < 0.01$) days to emergence of durum wheat. The cropping year and the combined effect of cropping years with cultivar did not affect the number of days of emergence under both production systems (Table 4).

Under the rain-fed production system, the days to emergence ranged between 6.5 and 10 days. The seeds of *Tesfaye* cultivar emerged late while *Dire*, *Donmateo*, *Fetan*, *Obsa*, and *Ude* cultivars emerged relatively early (Table 5). In the irrigated production system, the number of days to emergence of durum wheat cultivars ranged between 5 to 7 days (Table 5) where the cultivars *Bakalcha*, *Hitosa*, *Mangudo*, *Tate*, and *Tesfaye* emerged late while *Fetan*, *Gerardo*, *Toltu*, and *Ude* cultivars emerged relatively early. These separate research results indicated that the numbers of days to emergence were significantly affected by the cultivars in the rain-fed and irrigated production systems. The variations in days to emergence observed in the present study might be due to the genetic variability and the environmental adaptability of the tested cultivars. In this line, the previous research result also indicated that the days to emergence and seedling development were influenced by the genetic factors of the cultivars tested under the same environmental condition (Horváth *et al.*, 2023).

The result of the pair-wise T-test of the combined data over the years indicated that the irrigated production system reduced the number of days required for seed emergence of the durum wheat cultivars compared to the rain-fed production system by 20.5% (Table 6). The variations are obviously associated with higher temperatures (Figure 1) and suitable soil moisture during the irrigation season that accelerates the germination and development of seedlings. In this regard, increasing temperature by $1\ ^0$C leading to the enhancement of the enzymatic activities resulting the accelerated germination and seedling development of wheat (Sharma *et al.*, 2022). The previous research result also indicated that environmental factors affected the germination and seedling emergence of crops (Kołodziejek and Patykowski, 2015; Adeli *et al.*, 2022). Wu *et al*, (2012) reported that higher soil moisture and low temperatures decreased emergence day by 3 to 4 days compared to low moisture and high temperatures, which existed in irrigated production systems.

3.1.2. Days to flowering

The combined data analysis of variance over the years revealed that cultivar-influenced days to flowering under rain-fed ($p < 0.01$) and irrigated ($p < 0.05$) production systems. However, the cropping year and its combination with cultivars did not affect the number of days to flowering in the rain-fed as well as in the irrigated production systems (Table 4).

In the rain-fed production system, *Mangudo* cultivar flowered relatively late, which was statistically ($p < 0.01$) different compared to *Bakelcha*, *Bullalla* and *Toltu* cultivars. In contrast, *Bakalcha* cultivar flowered early in the rain-fed production system. Under the irrigated production system the *Dire* and *Toltu* cultivars recorded the highest number of days for flowering, which was significantly ($p < 0.05$) different compared to the days to flowering of *Donmateo*, *Gerardo*, *Mokiye* and *Were*r cultivars. The *Mokiye* cultivar recorded the lowest days to reach flowering in the irrigated sestet (Table 5). In both production systems, the number of days to flowering is affected by the tested cultivar and it might be due to the variable responses of the cultivars to the specific growing conditions associated with their genetic variability. In this regard, variation in days to flowering among cultivars associated with the genetic variability was also reported by Benaouda (2022).

The pair-wise T-test of the combined data over the years indicated that the irrigated production system reduced the days required to reach flowering compared to the rain-fed production system in durum wheat. Irrespective of cultivars, the rain-fed production system prolonged the number of days required to flower by 5.6% compared to the irrigated production system, which is associated with environmental variability (Table 6). As indicated in Figure 1, the average amount of rainfall recorded during the cultivated months was 862.6 mm while the amount of water applied to the irrigated production system was 585.4 mm (Table 3). This excess water under the rain-fed production system may contribute to the prolonged days of flowering. Conversely, the average temperature in the irrigation was relatively higher (Figure 1) compared to the rain-fed system, which contributed to the early flowering of durum wheat. These results are in agreement with other scholars who reported prolonged flowering of wheat plants under low temperatures and excessive soil moisture (Ndiso *et al.,* 2016; Chauhan *et al.,* 2019; Senapati *et al.*, 2021).

3.1.3. Days to physiological maturity

In the rain-fed system, the pooled data analysis of variance over the years indicates that cultivar and year had significantly ($p < 0.05$) affected the physiological maturity of durum wheat. However, the interaction effect of year and cultivar did not affect ($p > 0.05$) the number of days required for physiological maturity. Under the irrigated production system, the cultivar significantly affected the physiological maturity of durum wheat at $p < 0.01$. Conversely, the tested year and the interaction effect of year and cultivar did not affect the maturity of durum wheat (Table 4).

Under the rain-fed production system, the number of days to reach physiological maturity of the tested cultivars ranged from 109 to 115 days. *Ejersa* cultivar matured late while *Bekelcha, Bullalla, Dire*, and *Ude* cultivars matured earlier was statistically similar to all the tested cultivars except *Ejersa* cultivar (Table 5). Under the irrigated production system *Tesfaye* cultivar required a longer time to reach physiological maturity while *Bekelcha* and *Bullalla* cultivars matured earlier (Table 4). The current research results indicated that cultivars affected the maturity days of wheat even under different growing conditions. The differences in maturity of durum wheat observed in rain-fed as well as in irrigated production systems are associated with the genetics of the cultivars. In this regard, Tanin *et al*, (2022) also reported that wheat cultivars differ in the number of days required to reach physiological maturity.

The pair-wise T-test result revealed that the irrigated production system reduced the number of days required to reach the physiological maturity of durum wheat by 4.3% over the rain-fed system (Table 6). The early maturity of durum wheat in an irrigation production system compared to the rain-fed is associated with suitable environmental conditions. The application of water in the irrigated system was synchronized with critical stages of the crop that may enhance the growth and development and thus shorten the maturity of the crop. In addition, the average temperature in the irrigated production system was relatively higher compared to the temperature during the rain-fed experiment, which may accelerate the growth cycle and lead to shortening the maturity of the crop. In this regard, Mazengo *et al.* (2023) reported that the irrigated production system significantly accelerates the growth and development of wheat compared to the rain-fed production system. Similarly, Iwańska *et al.* (2020) also reported that wheat cultivars may need different growing conditions to express their genetic potential.

3.1.4. Number of productive tillers per plant

Under the rain-fed production system, the combined analysis of variance over the years showed that the year, cultivar, and their combination had significantly affected the number of productive tillers per plant at $P < 0.01$. In the irrigated production system, only the cultivar had a significant effect ($P < 0.01$) on the number of productive tillers per plant (Table 4).

In the rain-fed production system, *Utuba* cultivar recorded the highest number of productive tillers per plant, which was statistically similar to productive tillers produced by *Tesfaye* while the cultivars *Bekelcha*, *Bullalla*, and *Toltu* recorded the smallest number of productive tillers per plant (Table 5). Similarly, the cultivar *Utuba* recorded the highest number of productive tillers per plant in the irrigated production system as well, which is statistically similar to tillers produced by the cultivars *Mangudo* and *Tesfaye.* The number of productive tillers is one of the most important parameters that influence 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 of the cultivars observed in rain-fed as well as in the irrigated production system are related to the genetics of the cultivars. In this regard, research findings of various scholars also reported that wheat cultivars based on their genetic produce differ in their tillering capacities, which is in agreement with the findings of the present study (Liu *et al.,* 2020; Shang *et al.,* 2021).

The pair-wise 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. Irrespective of the cultivars, the irrigated production system increased the number of productive tillers per plant by 45.6% compared to the rain-fed production system (Table 6). The increase in productive tillers per plant in the irrigation production system is probably related to the environmental suitability where the application of water was based on the critical growth stage of the plants. The prevailing high temperature and the absence of diseases and insect pests may also contribute to the enhanced growth and development of the plants including the productive tillers per plant in the irrigated production system. The previous research result also indicated an increase in effective tillers of wheat cultivars due to increased temperature (Chavan *et al.,* 2022).

3.1.5. Plant height

The result of the combined data analysis over the years showed that cultivar ($p < 0.01$) and cropping years ($p < 0.05$) significantly affected the plant height of durum wheat while their interaction did not influence this parameter in the rain-fed production system. Under the irrigated system, the cultivar influenced the plant height ($p < 0.05$) while the cropping year and its interaction with the cultivar did not affect the plant height of durum wheat at $p > 0.05$ (Table 4).

The highest plant height was recorded from *Gerardo* cultivar while *Bekelcha* cultivar recorded the lowest plant height in rain-fed and irrigated production systems (Table 5). The plant height variations among durum wheat cultivars observed in rain-fed as well as in irrigated production systems could be related to genetic variations. These results are supported by the findings of Gao *et al.* (2020) who reported considerable variations in plant heights of different wheat cultivars. According to Góral *et al.* (2019) report the plant height of wheat is significantly affected by the genetic variability of the cultivars.

The pair-wise T-test analysis revealed that the irrigation production system increased the plant height by 8.5% compared to the same cultivars that were tested under the rain-fed production system (Table 6). The enhanced plant height of durum wheat in the irrigated production system compared to that of rain-fed in the present study could be attributed to the balanced water supply based on the growth stages of the plants and the prevailed higher temperature during the irrigated production system compared to the rain-fed production system. The findings of this study are supported by scholars who indicated that the amount of soil moisture and the genetic variations of cultivars affect the plant height of wheat (Degewione *et al.,* 2013; Branković *et al.,* 2015).

Table 4: ANOVA values for phenological and vegetative growth of durum wheat cultivars under the 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				
		DE	DF	PH	DM	PT/P	DE	DF	PH	DM	PTP
Replication	2	0.62	24.2	38.03	35.3	0.02	0.03	12.8	17.3	2.8	0.13
Year (Y)	1	4.80^{ns}	12.7^{ns}	456.3*	608*	33.0**	0.01^{ns}	39.7^{ns}	63.1^{ns}	2.7^{ns}	1.023^{ns}
Cultivar (C)	19	9.4**	193**	332.8**	22.3	13.2**	3.5**	84.0*	210.4*	46.8**	22.6*
Y*C	19	0.53^{ns}	0.8^{ns}	4.09^{ns}	12^{ns}	0.75**	0.3^{ns}	1.6^{ns}	1.5^{ns}	0.33^{ns}	0.09^{ns}
Error	78	1.16	55.68	80.87	7.07	0.11	0.7	12.88	48.2	11.1	0.36
Grand mean		7.7	72.22	84.95	111.7	2.58	6.12	68.17	92.8	106.9	4.74
CV (%)		14.01	10.33	10.59	2.38	12.79	13.3	5.26	7.48	3.11	12.71
DMRT (5%)		2.28	15.78	19.02	5.62	0.69	1.73	7.59	14.68	7.03	1.27

*ns, *and **, non-significant, and significant at P = 0.05 and 0.01, respectively, DF = Degree of freedom, DE = days to emergence, DF = days to flowering, PH = plant height, DM = days to maturity, PTP= Productive tiller per plant, Y*C = Interaction of year with cultivar, DMRT (5%) = Duncan's multiple range test at 5%t,* and *CV (%) = Percentage of coefficient of variation*

Table 5: Phenological and vegetative growth 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				
	Days of emergence	Days to flowering	Plant height (cm)	Days to maturity	Productive tillers/Plant	Days to emergence	Days to flowering	Plant height (cm)	Days to maturity	Productive tillers/Plant
Alemtena	7^{cd}	69^{a-c}	87^{a-e}	113^{ab}	2.8^{f}	6^{a-c}	70^{a-c}	93.0^{a-d}	107.0^{a-d}	5.0^{de}
Bakalcha	9.5^{ab}	63^{c}	70^{e}	109^{b}	1^{i}	7^{a}	65.5^{a-d}	81.0^{d}	102.5^{d}	3.0^{f}
Bullalla	7.5^{b-d}	65^{bc}	71.5^{de}	109^{b}	1^{i}	6.5^{a-c}	65^{b-d}	82.0^{cd}	102.5^{d}	3.0^{f}
Denbi	7^{cd}	70^{a-c}	85^{a-e}	111^{ab}	1.5^{hi}	6.3^{a-c}	65.5^{a-d}	90.5^{a-d}	104.5^{b-d}	3.0^{f}
Dire	6.5^{d}	71.5^{a-c}	80^{a-e}	109^{b}	1.5^{hi}	5.8^{a-c}	73^{a}	89.5^{b-d}	105.0^{a-d}	2.8^{f}
Donmateo	6.5^{d}	75^{a-c}	90^{a-d}	113^{ab}	2.5^{fg}	5.8^{a-c}	61^{d}	96.0^{a-c}	107.0^{a-d}	4.7^{de}
Ejersa	7^{cd}	74.5^{a-c}	87.5^{a-e}	115^{a}	2^{gh}	5.2^{bc}	72.5^{ab}	93.5^{a-d}	107.0^{a-d}	5.0^{de}
Fetan	6.5^{d}	73.5^{a-c}	72^{c-e}	110^{ab}	1.3^{i}	5^{c}	72^{ab}	86.5^{b-d}	103.5^{cd}	3.0^{f}
Gerardo	7^{cd}	72^{a-c}	98^{a}	113^{ab}	1.3^{i}	5^{c}	64^{cd}	105.0^{a}	107.0^{a-d}	3.3^{f}
Hitosa	8.5^{a-d}	81^{a}	90^{a-d}	110^{ab}	4^{c-e}	7^{a}	67^{a-d}	97.5^{ab}	109.0^{a-d}	6.0^{cd}
Mangudo	9.5^{ab}	82^{a}	89^{a-e}	114^{ab}	4.3^{cd}	7^{a}	71.5^{a-c}	95.0^{a-d}	111.0^{ab}	7.7^{ab}
Mokiye	7^{cd}	70^{a-c}	85.5^{a-e}	110^{ab}	2.5^{fg}	6^{a-c}	62^{d}	92.0^{a-d}	106.5^{a-d}	4.0^{ef}
Obsa	6.5^{d}	67^{a-c}	85.2^{a-e}	113^{ab}	1.3^{i}	6.1^{a-c}	71^{a-c}	91.5^{a-d}	106.0^{a-d}	3.0^{f}
Tate	9.5^{ab}	77.5^{a-c}	92^{ab}	114^{ab}	4.5^{bc}	7^{a}	67.5^{a-d}	99.5^{ab}	109.0^{a-d}	6.7^{bc}
Tesfaye	10^{a}	80.5^{ab}	90.5^{a-d}	113^{ab}	5^{ab}	7^{a}	66^{a-d}	98.0^{ab}	112.0^{a}	7.9^{ab}
Toltu	7^{cd}	64^{c}	78^{b-e}	111^{ab}	1^{i}	5^{c}	73^{a}	87.0^{b-d}	104.5^{b-d}	3.0^{f}
Ude	6.5^{d}	67.5^{a-c}	80.4^{a-e}	109^{b}	1.5^{hi}	5^{c}	69^{a-d}	90.0^{b-d}	105.0^{a-d}	3.0^{f}
Utuba	9^{a-c}	77^{a-c}	91^{a-c}	113^{ab}	5.5^{a}	6.8^{ab}	72.5^{ab}	99.5^{ab}	111.0^{ab}	8.8^{a}
Werer	9^{a-c}	76^{a-c}	89^{a-e}	112^{ab}	3.8^{de}	6.8^{ab}	65^{b-d}	95.5^{a-d}	110.0^{a-c}	6.0^{cd}
Yerer	7^{cd}	68.5^{a-c}	87.4^{a-e}	112^{ab}	3.5^{e}	6^{a-c}	70^{a-c}	93.0^{a-d}	107.0^{a-d}	5.8^{cd}
Grand mean	7.7	72.22	84.95	111.65	2.58	6.12	68.17	92.8	106.9	4.74
DMRT (5%)	2.28	15.78	19.02	5.62	0.69	1.73	7.59	14.68	7.03	1.27
CV (%)	14.01	10.33	10.59	2.38	12.79	13.32	5.26	7.48	3.11	12.71
MSE±	1.16	55.68	80.87	7.07	0.11	0.67	12.87	48.2	11.1	0.36
LS	**	**	**	*	**	*	*	*	**	*

ns, *and **, non-significant, and significant at P = 0.05 and 0.01, respectively, DMRT (5%) = Duncan's multiple range test at 5 percent, CV (%) = Percentage of coefficient of variation, MSE± = Mean square of error, and LS = Level of significance.

Table 6: Pair-wise T-test analysis of phenological and growth of durum wheat cultivars under the rain-fed and irrigated production systems (data combined over the 2020 and 2021 cropping years)

Tested parameter	IRRS	RFS	MD	SD	P_{value}	T_{test}		L.C.I 95%	U. C.I 95%
						T_{cal}	T_{tab}		
Days to emergence	6.12	7.7	-1.58	0.05	0.01	29.1	9.9	97.84	131.9
Days to flowering	68.17	72.22	-4.1	2.06	0.41	-1.02	0.2	-10.9	6.744
Days to maturity	106.9	111.7	-4.8	2.46	0.19	-1.89	0.8	-15.2	5.94
Plant height	92.8	84.9	7.9	2.08	0.06	3.76	1.8	-1.12	16.78
Productive tillers per plant	4.74	2.58	2.16	0.19	0.05	29.9	3.8	5.45	6.27

IRRS= Irrigation production system, RFS= Rain-fed production system, MD = Mean Difference, SD = Standard deviation, SE=Standard Error, L.C.I= Low confidential Interval at 95%, U.C.I= Upper confidential Interval at 95%.

3.2. Yield and yield-related responses of durum wheat cultivars in irrigated and rain-fed production systems

3.2.1. Plant height

The pooled data analysis of variance over the years showed that cultivar influenced the number of spikelets per spike of durum wheat in rain-fed ($P < 0.01$) and irrigated ($P < 0.05$) production systems. Conversely, the cropping year and its interaction with the cultivar did not influence ($P > 0.05$) this parameter in both production systems (Table 7).

In the rain-fed production system, the highest number of spikelets per spike was recorded from the *Mangudo* cultivar while the smallest was registered from *Denbi* and *Fetan* cultivars (Table 8). In the irrigated production system, *Mangudo* cultivar recorded the highest spikelets per spike while *Denbi* and *Fetan* cultivars were registered the smallest (Table 8). The variation of spikelets per spike between the tested cultivars within the production system is observably related to the genetic variability of the tested cultivars. In agreement with the results of the present study, Qiao *et al.* (2022) also reported that genetic factors of the cultivars affected the production of spikelets per spike of wheat.

The pair-wise T-test analysis indicated that the irrigated production system increased the number of spikelets per spike of durum wheat cultivars by 25.8% compared to the rain-fed production system (Table 9). The increment of spikelets per spike of durum wheat in the irrigated production system could be attributed to suitable soil moisture content during the critical period of the crop and higher temperature compared to the rain-fed production system. The previous research result also indicated that the genetic variation of the cultivars and environmental factors such as soil moisture content and temperature affect the spike architecture, arrangement of each spikelet, and number of spikelets per spike of wheat (Dixon *et al.*, 2018; Beral *et al.*, 2022).

3.2.2. Number of kernels per spike

The combined analysis of variance over the years revealed that cultivar and cropping year had affected ($p < 0.01$) the number of kernels per spike yet their interaction did not affect ($p > 0.05$) this parameter in the rain-fed production system. Under the irrigated production system the main effect of the cultivar affected ($P < 0.01$) the number of kernels per spike while the cropping year and its interaction with the cultivar did not affect ($P > 0.05$) this parameter of durum wheat (Table 7).

The number of kernels per spike of the tested cultivar under the rain-fed production system ranged from 18 to 40. In the rain-fed production system, the highest and the smallest numbers of kernels per spike were recorded from *Mangudo* and *Bakalcha* cultivars, respectively (Table 8). In the irrigated production system the number of kernels per spike of durum wheat ranged from 46 to 70. In the irrigated system the highest number of kernels per spike was recorded from the *Mangudo* cultivar while the smallest was registered from the *Fetan* cultivar (Table 8). The difference in the number of kernels per spike of the cultivars within each production system could be due to the genetic variability between the tested cultivars in both production systems. Genetic variation of wheat cultivars affects the production of kernels per spike (Kazan *et al.,* 2019), which is in line with the findings of the present study.

The pair-ways T-test analysis indicated that the number of kernels per spike in the irrigated production system increased by 42.1% compared to the rain-fed production system (Table 9). This is because the irrigated production system has suitable soil moisture content and temperature during the critical stage of the crop over the rain-fed production system. Research results also showed that the number of kernels per spike of wheat could be increased in the range of 36% to 56% under suitable environmental conditions including water availability (Mirbahar *et al.,* 2009; Kazan *et al.,* 2022).

3.2.3. Grain yield

In the rain-fed production system, the combined analysis of variance over the years revealed that the effect of cultivar ($p < 0.01$) and cropping years ($p < 0.05$) significantly affected the grain yield of durum wheat however; their combined effect did not affect this parameter ($p > 0.05$). Under the irrigated production system cultivar significantly affected ($p < 0.05$) the grain yield while the cropping year and its interaction with the cultivar did not affect ($p > 0.05$) this parameter (Table 7).

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 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 *Mangudo, Tesfaye, Utuba, Hitosa* and *Tate* cultivars, which were statistically similar when compared to each other while the lowest grain yield was recorded from *Bakalcha, Bullalla* and *Fetan* cultivars. In the irrigated production system the cultivars *Tesfaye, Mangudo* and *Utuba* recorded the highest grain yield while *Bakalcha* and *Bullalla cultivars* recorded the lowest grain yield (Table 8). The variation in grain yield among the durum wheat cultivars in both production systems could be due to the genetic variability of the tested cultivars. In line with the results of the present study, earlier research findings also showed that the yield of wheat is affected 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 40.9% compared to the rain-fed production system (Table 9). This grain yield variation is probably associated with environmental differences between the two production systems. Plants grown under an irrigated production system received irrigation water based on their critical growth stage (Figure 1 and Table 3) and the temperature under irrigation conditions was relatively higher that enhances the growth and development of plants leading to the enhanced grain yield compared to the rain-fed conditions where the rainfall was higher and the temperature was relatively lower. The absence of diseases and insect pests in irrigated production systems could also contribute to the enhancement of the grain yield of durum wheat. The results of the present study are supported by the findings of previous research where the grain yield of winter wheat in an irrigation production system increased by 40% compared to the rain-fed production system (Hordofa *et al.,* 2022). Similarly, increased wheat grain yield in irrigation production systems compared with rain-fed production systems was observed by other scholars (Xie *et al.*, 2017).

3.2.4. Biomass yield

The pooled data analysis of variance over the years showed that wheat cultivars influenced biomass yield of durum wheat under rain-fed ($p < 0.01$) and irrigated ($p < 0.05$) production systems. However, the cropping year and its interaction with cultivars did not affect ($p > 0.05$) the biomass yield of durum wheat in both production systems (Table 7).

The cultivars *Mangudo*, *Tesfaye*, *Utuba* and *Tat* in the rain-fed production system and the cultivars of *Tate*, *Utuba*, *Hitosa Mangudo*, and *Tesfaye* in the irrigated production system recorded the highest biomass yield per hectare. On the other hand, *Bakalcha* and *Bullalla* cultivars produced the lowest biomass yield in both production systems (Table 8). The biomass yield variation among the durum wheat cultivars observed in the present study could be due to the genetic variability between the tested cultivars. Such variability of cultivars in biomass yield production was also reported by Qin *et al.* (2019) and Maeoka *et al.* (2020).

Pair-wise T-test analysis of the combined data over the years showed that the irrigated production system increased the biomass yield of durum wheat cultivars by 36% compared to the rain-fed production system, which indicates the environmental suitability of the irrigated production system (Table 9). Plants grown under an irrigated production system received irrigation water based on their critical growth stage (Figure 1 and Table 3) and the temperature under irrigation conditions was relatively higher enhancing the growth and development of plants leading to the enhanced biomass yield compared to the rain-fed conditions where the rainfall was higher and the temperature was relatively lower. The absence of diseases and insect pests in irrigated production systems could also contribute to the enhancement of the biomass yield of durum wheat. The results of the present study are supported by the findings of Wang *et al.* (2019) where biomass yield was increased in the irrigated system compared to the rain-fed wheat production system.

Table 7: ANOVA values for grain yield and yield-related traits of durum wheat cultivars under the 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			
		NSS	NKS	BY (kg ha^{-1})	GY (kg ha^{-1})	NS/S	NK/S	BY (kg ha^{-1})	GY (kg ha^{-1})
Replication	2	0.18	25.5	859750	474142	2.78	23.12	2395750	4333
Year (Y)	1	4.80^{ns}	2284**	27000.0^{ns}	866490*	10.80^{ns}	37.9^{ns}	2207378^{ns}	25960^{ns}
Cultivar (C)	19	35.9**	345.6**	5617000**	1118000**	50.6*	353**	6483766*	3049121*
Y*C	19	1.17^{ns}	47.33*	0.0002^{ns}	28598.7^{ns}	2.27^{ns}	2.12^{ns}	1291165^{ns}	8063^{ns}
Error	78	3.02	14.56	993596	145022	5.13	32.25	2226177	431000
Grand mean		13.20	31.70	6758.1	2901.0	17.8	54.76	10562.0	4904.7
CV (%)		13.17	12.04	14.75	13.13	12.73	10.37	14.13	13.39
DMRT (5%)		3.68	8.07	2108.3	805.47	4.79	12.01	3155.8	1388.6

*ns, *and **, non-significant, and significant at P = 0.05 and 0.01, respectively, DF = Degree of freedom, NSS = number of spikelet per spike, NKS = number of kernel per spike, BY = biomass yield kilogram per hectare, GY = grain yield kilogram per hectare, Y*C = Interaction of year with cultivar, DMRT (5%) = Duncan's multiple range test at 5%, CV (%) = Percentage of coefficient of variation*

Table 8: 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)

	Rain-fed production system				Irrigation production system			
Cultivars	Number of spikelet/spike	Number of kernel/spike	Grain yield (kg ha^{-1})	Biomass yield (kg ha^{-1})	Number of spikelet/spike	Number of kernel/spike	Grain yield (kg ha^{-1})	Biomass yield (kg ha^{-1})
Alemtena	13.5^{b-f}	31.5^{b-d}	3040.9^{de}	7206^{d-f}	18.5^{b-e}	56.0^{b-g}	4585.0^{c-e}	11785^{a}
Bakalcha	12.0^{d-f}	17.5^{g}	667.5^{j}	1608^{k}	16.0^{de}	46.5^{g}	4101.7^{e}	8628^{b}
Bullalla	12.0^{d-f}	18.5^{fg}	805.0^{ij}	1931^{jk}	16.5^{de}	47.0^{g}	4300.0^{de}	9216^{ab}
Denbi	10.0^{f}	28.5^{de}	2175.0^{f-h}	5166^{f-i}	14.5^{e}	49.0^{fg}	4450.0^{de}	10001^{ab}
Dire	13.5^{b-f}	24^{d-g}	1637.5^{gh}	3871^{h-j}	17.5^{c-e}	50.5^{e-g}	4525.0^{de}	9681^{ab}
Donmateo	12.0^{d-f}	38.2^{ab}	4055.0^{bc}	9497^{a-c}	16.0^{de}	55.0^{c-g}	4700.0^{b-e}	10489^{ab}
Ejersa	13.0^{c-f}	37^{a-c}	3459.1^{cd}	8120^{c-e}	18.0^{c-e}	54.0^{c-g}	4602.5^{c-e}	10294^{ab}
Fetan	10.0^{f}	21.5^{e-g}	1375.0^{h-j}	3526^{i-k}	14.5^{e}	46.0^{g}	4400.0^{de}	9884^{ab}
Gerardo	13.0^{c-f}	36.7^{a-c}	2625.0^{ef}	6191^{e-g}	17.5^{c-e}	48.3^{fg}	4425.0^{de}	9943^{ab}
Hitosa	16.0^{a-c}	39^{ab}	4350.0^{ab}	9932^{a-c}	20.0^{b-d}	68.0^{ab}	5645.0^{a-d}	11716^{ab}
Mangudo	18.0^{a}	40^{a}	4925.0^{a}	11205^{a}	25.0^{a}	70.0^{a}	6200.0^{a}	11689^{ab}
Mokiye	11.0^{ef}	31.5^{b-d}	2442.0^{e-g}	5759^{f-h}	16.0^{de}	52.5^{d-g}	4540.0^{de}	10180^{ab}
Obsa	11.0^{ef}	25.8^{d-f}	1785.0^{gh}	4220^{g-i}	16.0^{de}	48.0^{fg}	4405.0^{de}	9835^{ab}
Tate	15.5^{a-d}	39^{ab}	4419.1^{ab}	10067^{a-c}	21.5^{a-c}	66.0^{a-c}	5940.0^{a-c}	12322^{a}
Tesfaye	17.0^{ab}	39.5^{ab}	4625.0^{ab}	10464^{a}	23.0^{ab}	63.0^{a-d}	6225.0^{a}	11680^{ab}
Toltu	10.5^{ef}	23.5^{d-g}	1490.0^{hi}	3548^{i-k}	15.0^{e}	48.0^{fg}	4325.0^{de}	9739^{ab}
Ude	10.5^{ef}	29.5^{c-e}	2097.5^{f-h}	4982^{g-i}	14.5^{e}	48.5^{fg}	4445.0^{de}	9989^{ab}
Utuba	16.0^{a-c}	38.5^{ab}	4560.0^{ab}	10364^{ab}	20.0^{b-d}	58.0^{a-g}	6025.0^{ab}	11852^{a}
Werer	15.5^{a-d}	37.6^{ab}	3975.0^{bc}	9244^{a-d}	19.0^{b-e}	59.5^{a-f}	5480.0^{a-e}	11644^{ab}
Yerer	14.0^{b-e}	36.8^{a-c}	3510.9^{cd}	8261^{b-e}	17.0^{c-e}	61.5^{a-e}	4775.0^{b-e}	10663^{ab}
Grand mean	13.20	31.70	2901.0	6758.1	17.8	54.76	4904.7	10562.0
DMRT (5%)	3.68	8.07	805.47	2108.3	4.79	12.01	1388.6	3155.8
CV (%)	13.17	12.04	13.13	14.75	12.73	10.37	13.39	14.13
MSE±	3.02	14.56	145022	993596	5.13	32.25	431000	2226177
LS	**	**	**	**	*	**	*	*

ns, *and **, non-significant, and significant at P = 0.05 and 0.01, respectively. DMRT (5%) = Duncan's multiple range test at 5 percent, CV (%) = Percentage of coefficient of variation, MSE± = Mean square of error, and LS = Level of significance

Table 9: Pair-wise T-test analysis of yield and yield related trait of durum wheat cultivars under the rain-fed and irrigated production systems (data combined over the 2020 and 2021 cropping years)

Tested parameter	IRRS	RFS	MD	SD	P_{Value}	T_{test}		L.C.I 95%	U. C.I 95%
						T_{cal}	T_{tab}		
Spikelet per spike	17.8	13.2	4.6	0.21	0.005	21.5	3.8	4.13	5.02
Kernel per spike	54.7	31.7	23.1	4.40	0.035	5.2	4.3	4.12	41.99
Grain yield (Kg ha^{-1})	4904.7	2901	2004	0.11	0.003	17.6	4.3	1.51	2.49
Biomass yield (kg ha^{-1})	10562	6758	3804	0.16	0.005	8.2	3.8	1.40	2.49

IRRS= Irrigation production system, RFS= Rain-fed production system, MD = Mean Difference, SD = Standard deviation, SE=Standard Error, L.C.I= Low confidential Interval at 95%, U.C.I= Upper confidential Interval at 95%

3.3. Grain quality responses of durum wheat cultivars to irrigated and rain-fed production systems

3.3.1. Thousand kernel weight

The combined data analysis of variance over the years showed that the cultivar and cropping years affected the thousand kernel weight of durum wheat under a rain-fed system ($p < 0.01$). However, under an irrigated production system the effect of cultivar significantly affected the thousand kernel weight of durum wheat ($p < 0.05$) while cropping year did not affect the thousand kernel weight of durum wheat ($p > 0.05$) (Table 10).

The thousand kernel weight of durum wheat ranged between 24 g and 48.3 g in the rain-fed production system and between 38.5 g and 51.8 g in the irrigated production system. The highest thousand kernel weight in both production systems was recorded from *Tate*, *Mangudo* and *Tesfaye* cultivars, which was statistically similar when compared to each other in the respective production system. The cultivars *Denbi*, *Fetan* and *Obsa*in rain-fed and the cultivars *Bakalcha* and *Bullalla* in irrigated production system recorded the lowest thousand kernel weights, which were statistically similar when compared to others in the respective production system (Table 11).

The variation on thousand kernel weight among the cultivars in both production systems could be associated with genetic variability and cultivar adaptability to the specific growing condition. The results of the present study are supported by the findings of Aktas, (2020) and Farkas *et al*. (2020) who reported that thousand kernel weights are mostly affected by the response of cultivars to the specific growing condition.

The pair-wise T-test analysis result of the combined data over the years revealed that the irrigated production system increased the thousand kernel weight of the durum wheat by 25% compared to the rain-fed production system (Table 12). Variations in the production system could be associated with suitable soil moisture content, relatively higher atmospheric temperature (Figure 1 and Table 3) and absence of diseases and insect pests in the irrigation production system could contribute to the improved vegetative growth and grain filling leading to enhanced thousand kernel weights. In this regard, Zhao *et al.* (2009) and Jabbour *et al.* (2023) reported that improper water supply during the grain-filling period reduces the thousand kernel weight which leads to reduced final grain yield of wheat.

3.3.2. Hectoliter weight

The result of the combined analysis of variance over the years revealed that cultivar influenced the hectoliter weight of durum wheat in both rain-fed ($p < 0.01$) and irrigated ($p < 0.05$) production systems. Cropping year and its interaction with cultivar in rain-fed conditions influenced ($p < 0.05$) the hectoliter weight of durum wheat, while in irrigated production systems this parameter was not influenced ($p > 0.05$) (Table 10).

The hectoliter weights of the tested cultivars ranged from 31.5 kg/hl to 48.8 kg/hl under the rain-fed while 59.3 kg/hl to 81.6 kg/hl under irrigated production systems. *Donmateo, Mangudo* and *Tate* in the rain-fed production system and *Tate* and *Mangudo* cultivars in the irrigated production system recorded the highest hectoliter weights while *Bakalcha* and *Bullalla* in both production systems recorded the lowest hectoliter weights (Table 11). The variation of the cultivars towards the hectoliter weight in both production systems could be due to their genetic variability, which is supported by the findings of Szuba *et al.* (2024) where the genetic makeup influences the chemical composition and nutritional value of including the hectoliter weight.

The pair-wise T-test analysis showed that the irrigated production system increased the hectoliter weight of durum wheat by 39.4% compared to the rain-fed production system (Table 12). This could be due to the suitable soil moisture content and increased average temperature prevailing in the irrigation production system that leads to enhanced grain filling and increased hectoliter weight over the rain-fed production system. In this regard, the previous studies 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 temperature that existed during the growing season of the crop (Panghal *et al.*, 2019; Marinciu *et al*., 2021).

3.3.3. Protein content

The combined analysis of variance over the years showed that cultivar influenced the protein content of durum wheat in the rain-fed ($p < 0.01$) as well as in the irrigated ($p< 0.05$) production system. However, cropping year and its interaction cultivar did not influence ($p > 0.05$) the protein content of durum wheat in both production systems (Table 10).

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. *Bakalcha*, *Toltu*, *Bullalla,* and *Fetan* cultivars recorded the highest protein content in both production systems, where the protein contents were statistically similar when compared to each other within the production system (Table 11). On the other hand, the cultivars *Mangudo* and *Tesfaye* recorded the lowest protein content in both production systems. Protein content is one of the most important quality parameters of wheat. However, the grain protein content of wheat is affected by the genetic factor of the cultivar (Ullah *et al.,* 2020; Alemu and Gerenfes, 2021), which is in agreement with the findings of the present study.

The combined pair-wise T-test analysis of the data revealed that the grain protein content of durum wheat in a rain-fed production system was 13.29% while it was 12.99% in the irrigated production system (Table 12). According to Aydoğan and Soylu (2017), the grain protein content of wheat ranges from 12.62 to 14.16% in rain-fed and from 11.53 to 13.85% in the irrigated production system, which is in line with the results of the present study.

The reduced protein content of the grains observed in the present study could be associated with the moisture stress observed during the grain-filling stage of durum wheat in the rain-fed production system. The grain filling stage of the tested cultivars in the rain-fed production system was recorded in October where the monthly average rainfall was 45.2 mm while that of the irrigated production system was in January where the crops were irrigated with 142.5 mm (Figure 1; Table 3). The results are in line with the findings of Javed *et al.* (2022) who reported water stresses during the grain-filling stage decrease grain yield while increasing the protein content of wheat. Kettani *et al.* (2023) also reported an increase in grain protein content under soil moisture stress. Proper management of soil moisture content during the grain filling period is critical to improving the wheat grain yield (Khan *et al.*, 2020, Liu, *et al*, (2024).

Table 10: ANOVA values for grain quality parameters of durum wheat cultivars under the 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		
		TKW	HLW	PC	TKW	HLW	PC
Year (Y)	1	61.78**	19.04*	0.06^{ns}	21.68^{ns}	10.44^{ns}	0.19^{ns}
Cultivar (C)	19	403**	202.51**	7.39**	88.50*	267.45*	10.95*
Y*C	19	10.99**	2.00*	0.01^{ns}	0.49^{ns}	1.15^{ns}	0.01^{ns}
Error	78	9.83	7.90	0.43	22.33	11.52	0.50
Grand mean		34.56	41.78	13.29	46.11	68.98	11.99
CV (%)		9.07	6.74	4.95	10.25	4.94	5.90
DMRT (5%)		6.63	5.96	1.39	9.99	7.20	1.49

*ns, *and **, non-significant, and significant at P = 0.05 and 0.01, respectively, DF= Degree of freedom, TKW = Thousand kernel weight, HLW = Hectoliter weight, PC =Percentage of protein content, Y*C = Interaction effect of year with cultivar, DMRT (5%) = Duncan's multiple range test at 5 percent, and CV (%) = Percentage of coefficient of variation*

Table 11: Grain quality response 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		
	Thousand kernel weight (g)	Hectoliter weight (kg/hl)	Protein content (%)	Thousand kernel weight (g)	Hectoliter weight (kg/hl)	Protein content (%)
Alemtena	42.0^{a-c}	46.7^{a-c}	13.4^{b-g}	47.8^{a-c}	72.0^{c-g}	11.1^{c-e}
Bakalcha	26.5^{hi}	31.5^{g}	14.9^{a}	38.5^{c}	59.8^{j}	13.6^{a}
Bullalla	28.5^{f-i}	34.1^{fg}	14.5^{a-c}	38.5^{c}	59.3^{j}	13.5^{a}
Denbi	24.0^{i}	36.6^{e-g}	13.6^{a-g}	45.2^{a-c}	60.5^{j}	12.9^{ab}
Dire	30.5^{f-i}	44.2^{a-d}	14.3^{a-d}	45.9^{a-c}	67.8^{d-i}	12.6^{ab}
Donmateo	41.0^{b-d}	48.9^{a}	13.2^{c-g}	46.4^{a-c}	71.5^{c-g}	10.7^{de}
Ejersa	45.0^{a-c}	44.4^{a-d}	13.4^{b-g}	46.9^{a-c}	66.4^{e-j}	12.5^{a-c}
Fetan	24.5^{i}	34.8^{fg}	14.2^{a-e}	45.9^{a-c}	63.9^{h-j}	13.5^{a}
Gerardo	33.3^{e-g}	32.9^{fg}	13.0^{d-g}	42.5^{a-c}	63.3^{ij}	12.9^{ab}
Hitosa	30.5^{f-i}	38.7^{d-f}	12.4^{g}	50.4^{ab}	74.6^{a-d}	10.3^{de}
Mangudo	48.6^{a}	48.8^{a}	10.9^{h}	51.8^{a}	79.4^{ab}	9.8^{e}
Mokiye	33.5^{e-g}	45.6^{a-c}	13.6^{a-g}	43.9^{a-c}	60.4^{j}	11.6^{b-d}
Obsa	26.0^{hi}	42.2^{c-e}	13.7^{a-g}	45.5^{a-c}	66.0^{f-j}	13.1^{ab}
Tate	48.3^{a}	48.3^{ab}	12.6^{fg}	50.5^{ab}	81.6^{a}	10.1^{e}
Tesfaye	46.9^{ab}	47.5^{a-c}	10.6^{h}	51.3^{a}	76.6^{a-c}	9.9^{e}
Toltu	28.8^{f-i}	37.9^{ef}	14.6^{ab}	40.8^{bc}	65.5^{g-j}	13.6^{a}
Ude	27.0^{g-i}	36.7^{e-g}	13.9^{a-f}	46.5^{a-c}	73.9^{b-d}	12.5^{a-c}
Utuba	35.0^{d-f}	46.3^{a-c}	13.7^{a-g}	47.5^{a-c}	73.0^{b-f}	12.7^{ab}
Werer	38.8^{c-e}	46.9^{a-c}	12.7^{fg}	49.5^{ab}	73.4^{b-e}	10.6^{de}
Yerer	32.5^{e-h}	42.5^{b-e}	12.8^{e-g}	47.3^{a-c}	70.9^{c-h}	12.4^{a-c}
Grand mean	34.56	41.78	13.29	46.11	68.98	11.99
DMRT (5%)	6.63	5.96	1.39	9.99	7.20	1.49
CV (%)	9.07	6.74	4.95	10.25	4.94	5.90
MSE±	9.83	7.90	0.43	22.33	11.52	0.50
LS	**	**	**	*	*	*

ns, *and **, non-significant, and significant at P = 0.05 and 0.01, respectively, DMRT (5%) = Duncan's multiple range test at 5%, CV (%) = Percentage of coefficient of variation, MSE± = Mean square of error, and LS = Level of significance

Table 12: Pair-wise T-test analysis of grain quality of durum wheat cultivars under the rain-fed and irrigated production systems (data combined over the 2020 and 2021 cropping years)

Tested parameter	IRRS	RFS	MD	SD	P_{value}	T_{test}		L.C.I (95%)	U. C.I (95%)
						T_{cal}	T_{tab}		
Thousand kernel weight (g)	46.1	34.56	11.5	1.1	0.05	10.5	4.3	9.25	13.84
Hectoliter weight (kg/hl)	68.98	41.78	27.2	0.4	0.05	67.9	4.3	26.36	28.04
Protein content (%)	11.99	13.29	-1.3	0.3	0.04	-4.4	2.9	-2.59	-0.05

IRRS= Irrigation production system, RFS= Rain-fed production system, MD = Mean Difference, SD = Standard deviation, SE=Standard Error, L.C.I= Lower confidential Interval at 95%, U.C.I= Upper confidential Interval at 95%

4. Conclusion

The results of the present study clearly showed that cultivars influenced the growth, yield and quality of durum wheat. The performance of cultivars under the irrigated farming system was much better compared to the rain-fed production system. Accordingly, the irrigated production system increased the plant height (8.5%), productive tillers per plant (45.6%), spikelet per spike (25.8%), kernel 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 cultivars *Mangudo*, *Tesfaye*, *Utuba*, *Tate*, and *Hitosa* recorded the highest grain yield while the cultivars *Bakalcha*, *Toltu*, *Bullalla*, *Fetan*, *Ude* and *Utuba* recorded the highest grain protein content in both irrigated and rain-fed conditions. Therefore, the cultivars *Tesfaye*, *Mangudo*, *Utuba*, *Tate*, and *Hitosa* could be recommended for irrigated as well as for rain-fed production systems for enhancing the productivity of durum wheat in the study area and areas with similar agro-ecology.

Data availability statement

Data will be made available on request.

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Conflicts of interest

The authors declared that there is no conflict of interest.

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