Optimizing Nitrogen Fertilization for Barley Crop at Full and Deficit Irrigation in the Arid Region

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ABSTRACT

Background: Nitrogen and water are two major limiting factors that affects the growth and yield of barley. Optimization of nitrogen application is crucial in enhancing barley yield and nitrogen use efficiency while minimizing the negative effects of its intense application on human health and the environment. However, the crop yield response to nitrogen application rates differ under different irrigation conditions owing to the complementary relationship between nitrogen and water. Therefore, it is vital to study the impact of different nitrogen application rates on improving barley growth and yield under full as well as deficit irrigation to select the best field management option, thereby enhancing sustainable agriculture.

Methods: The present study investigated the impact of three nitrogen application rates [0 (control), 50 and 100 kgN/ha)] at two irrigation rates corresponding to 100% and 75% crop evapotranspiration (ET_c) on the growth, yield and nitrogen use efficiency of barley. Stable isotopic technique was used to determine the nitrogen use efficiency.

Result: The nitrogen application rate enacted a significant impact on plant height, number of plants/m^2, number of spikes/m^2, biomass yield and nitrogen use efficiency; whereas irrigation rates significantly affected the plant height, number of plants/m^2, spike length, number of spikes/m^2 biomass yield, grain and straw yield. In addition, a significant interaction between irrigation and nitrogen was observed for all the studied parameters except plant height, spike length, straw yield and total nitrogen uptake. The deficit irrigation 75% ET_c with 50 kgN/ha presented the highest nitrogen use efficiency (37.56%), but the total biomass yield was reduced by 37% in comparison to 100% ET_c irrigation. Thus irrigation and fertilization combination of 100% ET_c with 50 kgN/ha was identified as the best irrigation and fertilization practice producing highest biomass yield, grain yield and straw yield in barley with a nitrogen use efficiency of 20.48%.

Key words: Barley, Deficit irrigation, Nitrogen use efficiency, Nitrogen-15 isotope.

INTRODUCTION

Nitrogen fertilization holds paramount importance in agriculture and plays a vital role in crop production and ecosystem management (Rimmi *et al.*, 2023). It is a critical component of amino acids, proteins, chlorophyll and nucleic acids and plays a significant role in supporting the overall growth, development and reproduction of plants (Chen *et al.*, 2022). Maximizing crop yields through nitrogen fertilization can enhance the economic viability of farming operations. Optimizing nitrogen fertilization is a crucial component of sustainable farming, helping to improve food security while safeguarding the environment and natural resources (Abdelaal *et al.*, 2019; Spiertz, 2010). It ensures that crops receive the right amount of nitrogen for their specific needs, leading to higher yields and improved agricultural productivity. The recent research reported the overuse of nitrogen in Kuwait creating around 100 kg excess nitrogen per hectare (Lassaletta *et al.*, 2014). Barley (*Hordeum vulgare* L.), which is mainly used for making bread and as animal feed and forage in Kuwait requires large amounts of nitrogen to achieve a higher yield (Hafez and Abou El Hassan, 2015). Globally, it ranks fourth in cereal production after maize, wheat and rice (FAO, 2013) and is included in the list of the priority crops in the Agriculture Master Plan of the State of Kuwait (KISR, 1996). Mostly nitrogen fertilizers are added in excessive amounts by the farmers to intensify barley production which results in environmental loss *via* nitrate leaching, ammonia volatilization and nitrous oxide emissions (Mahmoud *et al.*, 2021). Previous research reported that around 60% of the fertilizer applied is either lost to the atmosphere, or groundwater or remained in the soil, while only 40% of the fertilizer applied is taken up by the crop (Anas *et al.*, 2020). In addition, it leads to diminishing returns and economical inefficiency that necessitates a significant increase in the efficiency of nutrient use to increase crop productivity at a minimum cost. Thus, it is critical to optimize nitrogen

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fertilization to produce more crops per unit of nitrogen fertilizer applied and thereby reduce production costs.

Water scarcity is a major limiting factor in enhancing crop production in Kuwait. The unavailability of permanent surface water and underground freshwater resources, in addition to the deterioration of the quantity and quality of groundwater, exacerbates the water crisis in Kuwait. A steady increase was found in the withdrawal of agricultural water of Kuwait from 0.32 billion m^3 per year in 1994 to 0.78 billion m^3 per year in 2017, growing at an average annual rate of 34.53%. A similar increase was observed in the consumption of fertilizer in Kuwait through 1999-2018 period ending at 1,059.5 kg per hectare in 2018 (World Data Atlas, 2018). Previous reports have shown that improper agricultural management practices could lead to a loss of up to 70 to 80% of the added nitrogen in rain-fed conditions and 60 to 70% in irrigated fields (Ladha *et al.*, 2005; Robertz, 2008). Nitrogen and water are complementary factors controlling crop growth and development (Palmroth *et al.*, 2013). The plant response to increasing doses of one of these factors is best when the other factor is not limited. Therefore, an integrated approach for fertilizer and water management is vital in improving yield as well as nitrogen use efficiency (Kumar *et al.*, 2020).

Kuwait is an arid country with less fertile soil lacking sufficient organic matter content required to support crop growth. Thus application of nitrogen fertilizer is required to promote vigorous plant growth and subsequent yield. Poor farming practices accompanied by improper water and fertilizer management practices drastically affects the plant productivity. It possesses a threat to the environment and sustainability of the agriculture production activity in Kuwait. Several previous studies have been focused on the single effects of nitrogen or irrigation application rates on the growth, yield and nitrogen use efficiency of barley (Adebayo *et al.*, 2021; Al-Menaie *et al.*, 2021; El-Nakhlawy *et al.*, 2018). However, scanty information is available on the barley yield, nitrogen use efficiency under different combination of irrigation and nitrogen rates. An elaborate understanding of how different crops respond to nitrogen fertilizer could be crucial for planning, screening and executing of future field trials. Thus the study investigated the effect of three different nitrogen treatments (0, 50, 100 kgN/ha) under two irrigation regimes (100% and 75% ET_c) on growth, yield and nitrogen use efficiency of barley under Kuwait arid conditions for two growing seasons (2020-2021 and 2021-2022).

MATERIALS AND METHODS

Forage crops establishment

The study was conducted at KISR Station for Research and Innovation-KSRI (29.3156$^{238}_{92}$ N, 47.8403$^{238}_{92}$ E), Kuwait at Kabd. The barley variety Kuwait 3 was selected for the experiment taking into consideration its high growth and yield performance as well as better adaptability to Kuwait's environmental conditions (Al-Menaie *et al.*, 2019). The selected barley variety was subjected to three different nitrogen rates (*i.e.* 100 kgN/ha, 50 kgN/ha and 0 kgN/ha) under two irrigation rates (100% ET_c, 75% ET_c). Split plot randomized complete block design was used to conduct the experiment from November 2020-March 2021 and November 2021-March 2022. The long term averages as well as monthly average for precipitation in Kuwait is presented in Fig 1 and 2. Two irrigation rates formed the main plots. The subplots were constituted by three different nitrogen treatments. The selected barley cultivar was planted via strip seeding method within a plot area of 21 m^2 for each of the treatments which were triplicated. The results are presented as the average of two seasons.

A sprinkler irrigation system with an automatic timer was used to irrigate the experimental plots. Irrigations rates were based on reference evapotranspiration (ET_0) estimated using daily measurements of maximum and minimum air temperature and relative humidity, average wind speed and total solar radiation. The Penman-Monteith method, as described in the commonly used FAO-56 reference (Allen *et al.*, 1998), was used to estimate ET_0 and actual evapotranspiration by the crop (ET_c) using the crop coefficient (k_c) for barley:

$$ET_c = k_c \times ET_0$$

Nitrogen, phosphorous and potassium fertilizers were broadcasted in the plots. Phosphorous was applied in the form of triple superphosphate [$(Ca(H_2PO_4)_2.H_2O)$] containing 43-44% P_2O_5 @ 150 kg P_2O_5 ha^{-1} during land preparation stage. Potassium was added at the rate of 120 kg K_2O ha^{-1} in the form of potassium sulfate (K_2SO_4) fertilizer (50% K_2O) as two equal doses at tillering and heading stages. The nitrogen in the form of urea [$(CO(NH_2)_2$] containing 46% N was applied @ 0 kgN/ha (control), 50 kgN/ha and 100 kgN/ha in 10 split applications at 10 days interval starting after the emergence of the seedling to just before heading. Split application of nitrogen fertilizer is a common local practice as the soil texture is sandy. One-time application of nitrogen fertilizer might lead to significant loss of fertilizer through leaching during daily irrigation practice.

Determination of nitrogen use efficiency

Plant growth and yield parameters including plant height, number of plants/m^2, spike length, number of spikes/m^2, grain yield, harvest index, straw yield, biomass yield was determined. Stable nitrogen-15 isotope was used to determine the nitrogen use efficiency using previously established equations (Zapata, 1990). Micro-plots of 0.5 m × 0.5 m were used for nitrogen-15 calculation. At physiological maturity, whole plant samples were collected from each of the nitrogen-15 labeled plot to calculate the total nitrogen-15 uptake. For dry matter production, plant samples were collected from area treated with non-labelled urea. Wet digestion method was used to determine the total nitrogen using Kjeldahl apparatus. Subsamples obtained from the grain and shoot from the labeled microplots at harvest were analyzed for nitrogen-15 analysis calculation of atomic N excess at International Atomic Energy Agency (IAEA) laboratories, Seibersdorf. The proportion of enriched isotopic N15/N14 was estimated using mass spectrometer and the percentage of nitrogen in the plant tissues, the nitrogen derived from fertilizer (Ndff), nitrogen derived from soil (Ndfs), total nitrogen absorbed N-uptake and the utilization rate of added nitrogen fertilizer N-recovery were determined for all treatments. The data obtained was used to calculate nitrogen use efficiency (NUE) using following equations (Zapata, 1990):

$$\%\text{Ndff} = \frac{\%\text{ N15 a.e. plant sample}}{\%\text{ N15 a.e. labeled fertilizer}} \times 100$$

$$\text{Nupdff} = \text{Nuptake} \times \%\text{Ndff}$$

$$\text{NUE} = \frac{\text{Nupdff}}{\text{Rate of N applied}} \times 100$$

Statistical analysis

Multifactor analysis of variance was performed to determine any significant difference in the mean values of the dependent variable under different irrigation as well as nitrogen treatments using Statistical Package for Social Sciences (SPSS) software. Treatments displaying significant differences were subjected to Duncan's multiple range test (DMRT) for mean separation at a 95% confidence level.

RESULTS AND DISCUSSION

Soil analysis

The soil at the experimental site was sandy in texture (98.6% sand, 1% silt and 0.4% clay) at soil depths of 0 to 30 cm. The subsurface (30 to 60 cm) contained 93.6% sand, 6% silt and 0.4% clay, whereas soil samples collected from 60 to 90 cm depth had 91.6% sand, 6% silt and 2.4% clay. The 90 to 120 cm soil depth contained 91.6% sand, 4% silt and 4.4% clay. All three depths are classified as sandy textures (Soil Science Division Staff, 2017). The results of soil chemical analyses (120 cm depth) are presented in Table 1.

Growth and yield parameters

The yield and growth performance, as well as nitrogen use efficiency of the barley crop variety Kuwait 3 subjected to three different nitrogen applications under two different irrigation rates, are given as the following tables:

Plant height

The data showed that irrigation application rates had a significant effect on the plant height ($p \leq 0.001$). Average plant height at 75% ET_c was 11.80% higher than those plants irrigated at 100% ET_c. Plant height also varied significantly between the nitrogen treatments ($p \leq 0.01$) presenting taller plants with the nitrogen application rate of 50 kgN/ha (Table 2). However, no significant interaction was found between irrigation and nitrogen treatments.

Number of plants/m^2

The irrigation ($p \leq 0.001$) and nitrogen treatments ($p \leq 0.01$) significantly affected the number of plants/m^2. In addition, an interaction was noted between irrigation and nitrogen treatments. Both irrigation treatments recorded the highest values with 50 kgN/ha (Table 3). However, a significant difference was not noted between the nitrogen treatments at 75% ET_c.

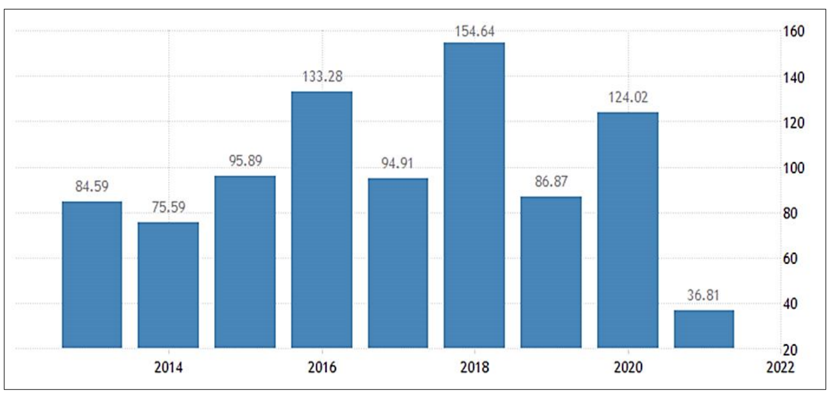

Fig 1: Long term average precipitation in Kuwait. (Source: Tradingeconomics.com).

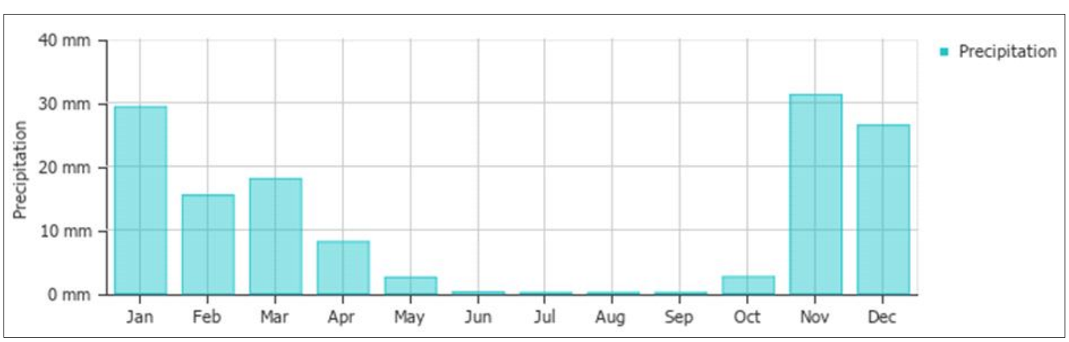

Fig 2: Monthly average precipitation in Kuwait. (Source: Weather and climate.com accessed on 5 November 2023).

Table 1: Soil physical and chemical analysis.

Parameters		Sample depth (cm)			
		0 to 30	30 to 60	60 to 90	90 to 120
	pHs	7.5	7.5	7.6	7.6
	EC_e (mS/cm)	3.30	2.13	3.26	3.07
	TDS (mg/l)	2112.0	1363.2	2086.4	1964.8
Cations (mg/kg)	Ca^{+2}	107.03	88.18	152.46	119.13
	Mg^{+2}	13.30	13.15	22.51	40.16
	K^+	15.23	17.16	22.42	8.35
	Na^+	74.58	15.87	9.79	9.56
Anions (mg/kg)	Cl^{-1}	154.29	26.28	25.77	18.37
	CO_3^-	<10	<10	<10	<10
	HCO_3^-	98.99	33.59	15.40	12.48
	NO_3^-	1.60	3.60	1.60	1.20
	NO_2^-	0.52	0.84	0.80	0.80
	PO_4^{-3}	20.00	76.00	16.00	<10

Table 2: Effect of different irrigation levels and nitrogen rates on plant height (cm).

Nitrogen treatments	Irrigation treatments		
	75% ET_c	100% ET_c	Mean
0 kgN/ha	69.75	61.50	65.62^a
50 kgN/ha	80.50	74.75	77.62^b
100 kgN/ha	72.50	63.00	67.75^a
Mean	74.25^d	66.41^c	70.33

a,b,c, d: Mean values with different superscripts in each column were significantly different (p≤0.05).

Table 3: Effect of different irrigation levels and nitrogen treatments on the number of plants/m^2.

Nitrogen treatments	Irrigation treatments		
	75% ET_c	100% ET_c	Mean
0 kgN/ha	250^a	452^b	350
50 kgN/ha	253^a	461^b	357
100 kgN/ha	244^a	336^a	290
Mean	249	416	333

a,b,c: Mean values with different superscripts in each column were significantly different (p≤0.05).

Table 4: Effect of different irrigation levels and nitrogen treatments on the number of spikes/m^2.

Nitrogen treatments	Irrigation treatments		
	75% ET_c	100% ET_c	Mean
0 kgN/ha	170^a	330^b	250
50 kgN/ha	165^a	314^b	239
100 kgN/ha	165^a	205^a	185
Mean	167	283	225

a,b,c: Mean values with different superscripts in each column were significantly different (p≤0.05).

Number of spikes/m^2

The statistical analysis revealed a significant effect of irrigation (p≤0.001) and nitrogen (p≤0.001) treatments on the number of spikes/m^2. The 100% ET_c irrigation application rate increased the number of spikes/m^2 by 24% when compared to the plants irrigated at 75% ET_c (Table 4). Similarly, number of spikes/m^2 decreased with the increasing nitrogen application rates. In addition, the significant interaction noted between irrigation and nitrogen (p≤0.001) revealed the highest value at 100% ET_c for each of the nitrogen treatments.

Biomass yield

The irrigation (p≤0.001) and nitrogen treatments (p≤0.05) had a significant effect on the biomass yield (Fig 3). The biomass yield with 100% ET_c was 31% higher in comparison to the yield produced at 75% ET_c level. In addition, a significant interaction was also found between irrigation and nitrogen (p≤0.05). The plants irrigated with 100 % ET_c under 50 kgN/ha presented the highest yield.

Grain yield

The grain yield varied significantly between irrigation rates (p≤0.05), displaying higher values with 100% ET_c. In addition, a significant interactive effect was noted between irrigation and nitrogen which revealed the highest value at 100% ET_c coupled with 50 kgN/ha (Fig 4). In contrast to 100% ET_c, the nitrogen treatment 100 kgN/ha presented the highest grain yield 75% ET_c with deficit irrigation.

Straw yield

The dry straw yield varied significantly between the two irrigation application rates (p≤0.05) producing the highest yield at 100% ET_c. It was increased by 28% in comparison to its value under 75% ET_c (Fig 5). However, the nitrogen treatments did not impose any significant effect on straw yield and no significant interaction was noted between these independent factors.

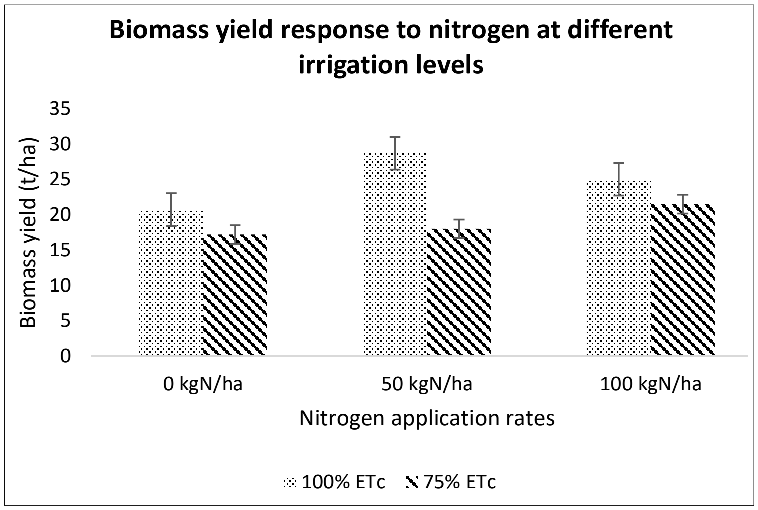

Fig 3: Effect of different irrigation and nitrogen treatments on the biomass yield (t/ha).

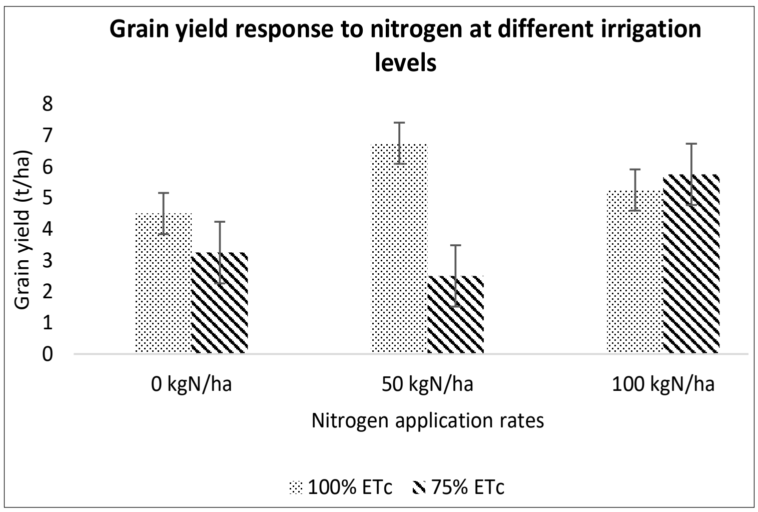

Fig 4: Effect of different irrigation and nitrogen treatments on grain yield (t/ha).

Nitrogen use efficiency

The nitrogen treatments ($p\leq0.05$) imposed a significant effect on the nitrogen use efficiency, whereas it did not vary significantly between the irrigation treatments ($p\geq0.05$). The nitrogen use efficiency of plants at 50 kgN/ha was 72% higher than those at 100 kgN/ha (Table 5). However, a significant interaction was noted between irrigation and nitrogen ($p\leq0.05$) presenting the highest nitrogen use efficiency at 75% ET_c level with 50 kgN/ha.

Over use of nitrogen fertilizers results in environmental pollution, eutrophication, greenhouse gas emissions, reduced biodiversity, soil biodegradation, increased production costs and also impose cytotoxic effects (Rimmi *et al*., 2023; Arora and Verma, 2023). The study evaluated the barley yield performance under 100 as well as 50 kgN/ha with full and deficit irrigation. A significant interaction was noted between nitrogen and irrigation application levels which reported the highest biomass and grain yield under reduced nitrogen application of 50 kgN/ha at 100% ET_c. The yield response curve for nitrogen application displayed an increase till 50 kgN/ha followed by a decline at 100 kgN/ha. Considering irrigation treatments, significantly higher biomass, grain as well as straw yield was noted with 100% ET_c irrigation level. Deficit irrigation reduced the number of plants/m^2 as well as number of spikes/m^2 as major carbon portion would be dedicated to root growth to access and acquire more water (Meier *et al*., 2018). Each of the nitrogen treatments recorded lower biomass, yield and straw yield values under deficit irrigation when compared to full

Table 5: Effect of different irrigation and nitrogen treatments on nitrogen use efficiency (%).

Nitrogen treatments	Irrigation treatments		
	75% ET_c	100% ET_c	Mean
50 kgN/ha	37.56^b	20.48^a	29.02
100 kgN/ha	12.03^a	21.54^a	16.78
Mean	24.79	21.01	22.90

a,b,c,: Mean values with different superscripts in each column were significantly different ($p\leq0.05$).

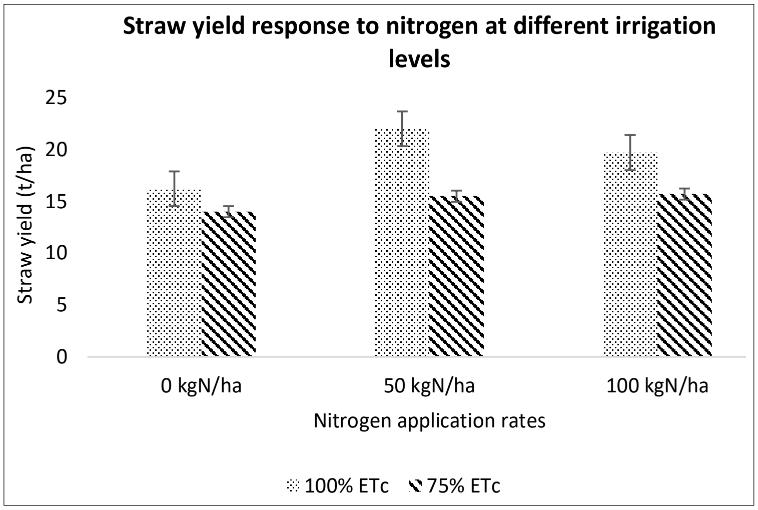

Fig 5: Effect of different irrigation and nitrogen treatments on straw yield (t/ha).

irrigation. However, the study was not able to identify the nitrogen rate producing the maximum achievable yield under deficit irrigation as the biomass, grain and straw yield increased with the increasing nitrogen application rates. As much of the photo assimilates could have been used in enhancing the root biomass rather than grain filling, a higher nitrogen application rate of 100 kgN/ha was required to produce higher biomass, grain and straw yield in crops at deficit irrigation (Boudiar *et al.*, 2020).

Thus the study revealed the potential of reduced nitrogen application rate of 50 kgN/ha under full irrigation (100% ET_c) in presenting improved barley yield when compared to 100 kgN/ha under Kuwait's environmental conditions. This implies that lower nitrogen application rate of 50 kgN/ha, could produce higher yield in barley if water is not limiting. The enhanced cell division, leaf area, transpiration and photosynthesis under full irrigation could enhance crop yield (Zhang *et al.*, 2015; Hafez and Abou El Hassan, 2015; Hoseinlou *et al.*, 2013; Liu *et al.*, 2013). However, the farmers need to test the soil fertility status before application of nitrogen fertilizers. Nitrogen use efficiency along with crop yield is an important factor to be considered in Kuwait's less fertile soil with little organic matter content to increase the economic profitability as well as environmental safety. With full irrigation, 20.48% nitrogen use efficiency was noted under 50 kgN/ha which did not vary significantly from that under 100 kgN/ha (21.54%). The absence of significant difference between the nitrogen use efficiency values under 50 and 100 kgN/ha nitrogen treatments under full irrigation could be due to the leaching of nitrate under increased water availability (Hafez and Kobata, 2012). Although nitrogen use efficiency was higher with 50 kgN/ha at deficit irrigation (75% ET_c.) in the study, the total biomass yield was reduced by 37% when compared to its performance at 100% ET_c. Deficit irrigation could enhance nitrogen translocation from soil to grain due to enhanced root biomass, which leads to higher sink nitrogen content (Xu *et al.*, 2006; Sinclair *et al.*, 2000). Higher nitrogen application rates decrease nitrogen use efficiency value in crops as the supply of nitrogen exceeds the actual plant requirement (Dhaka *et al.*, 2020; Hafez and Abou El Hassan, 2015). The nitrogen harvest index, nitrogen use efficiency, nitrogen recovery efficiency and nitrogen utilization efficiency increase under decreasing nitrogen rates (Beatty *et al.*, 2010; Arduini *et al.*, 2006; Rutkowska *et al.*, 2014). In contrast, several other studies have reported increased agronomic nitrogen use efficiency with the increasing supply of nitrogen (Timsina *et al.*, 2001; Pirmoradian *et al.*, 2004). Thus the selection of the best irrigation and fertilization pattern will depend on the water availability, cost of water, irrigation cost, soil fertility and input to yield price ratio in the region. Thus the study demonstrated the potential of reduced nitrogen application rate of 50 kgN/ha under 100% ET_c full irrigation condition to improving barley production in arid regions like Kuwait.

CONCLUSION

Proper nutrient management is crucial for sustainable agriculture, ensuring that crops receive the nutrients they need while minimizing negative environmental and economic impacts. The study recommends selecting fertilization and irrigation combination of 100% ET_c with 50 kgN/ha as the best field management option in improving barley yield with a nitrogen use efficiency of 20.48% under Kuwait's arid conditions. The results thus provide a baseline for studies intended to improving resource use efficient barley production in Kuwait and other regions with similar soil and environments.

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Conflict of interest

The authors declare no conflict of interest.

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