Ciftci *et al. BMC Plant Biology* (2025) 25:943
https://doi.org/10.1186/s12870-025-06921-z

BMC Plant Biology

RESEARCH Open Access

Grain yield and nutritional properties of buckwheat (*Fagopyrum esculentum* M.) grown with varying nitrogen doses and irrigation levels

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Abstract
Buckwheat has gained high demand and popularity worldwide in recent years. There are very few studies on the combined use of irrigation and nitrogen applications for the plant. In this study, the effects of different nitrogen dose (0, 30, 60, 90 kg ha^{-1}) and irrigation levels (50%, 75%, 100% of ETo value calculated with the use of evaporations from Class-A pan) applied via fertigation on water use, yield and grain nutritional properties in buckwheat were investigated. The study was carried out in 2020–2021 according to the randomized block design with 3 replications for two years. The highest grain yield was obtained with 100% irrigation level and 90 kg ha^{-1} nitrogen dose. The increase in nitrogen doses caused significant increases in crop water productivity (CWP) and irrigation water productivity (IWP) values. Plant water consumption (ET) varied between 339 (I0×N50) − 617 (I100×N90) mm. Yield response factor (ky) was determined to be between 1.32 for N0 and 1.49 for N30 according to nitrogen doses, and it was determined that the buckwheat plant was sensitive to water stress. The concentrations of significant constituents, including protein, resistant starch, and fatty acids (oleic acid, linoleic acid), were augmented with elevated irrigation levels and nitrogen fertilization. In addition, mineral contents (Ca, Mg, Fe, Zn, P) increased significantly with increasing irrigation and nitrogen doses. As a result, 100% irrigation level and 90 kg ha^{-1} nitrogen dose are recommended in buckwheat cultivation for optimum grain yield and nutrient content. It was determined that these applications provided the most suitable results in terms of both quality and yield.

Keywords Buckwheat, Irrigation, Nitrogen fertilization, Yield, Biochemical components, Mineral contents

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Introduction

Buckwheat is a grain-like plant, classified as a pseudocereal, that is cultivated in many countries around the world. Its significance in international trade is on the rise [1]. Globally, it is utilized to create gluten-free bread, noodles, pasta, cakes, biscuits, crepes, pancakes, and breakfast cereals [2]. The buckwheat plant plays an important role in producing various products, including wine, alcohol, vinegar, and tea. One of the notable qualities of buckwheat is its balanced amino acid composition, which contributes to its high protein quality. Additionally, buckwheat is an excellent source of dietary fiber, classified as a non-starch polysaccharide [3], and it also provides essential micro-minerals such as zinc, copper, and manganese [4].

With economic development, the demand for high-quality food continues to rise [5]. The yield and quality of agricultural products are influenced not only by their genetic makeup but also by environmental factors such as soil moisture, nutrients, climate conditions, and farming practices [6]. Among these factors, water and nitrogen play a critical role in determining crop yield and quality. Optimizing their use is essential for sustainable agricultural production. Since water and nitrogen are considered the most significant and manageable factors, implementing an effective management strategy for both is crucial. Such strategies can enhance crop quality, improve water efficiency, increase nitrogen use efficiency, and sustain overall yield [7].

Nitrogen is essential for high-yield agriculture. The application of nitrogen fertilizer not only increases crop yields but also enhances the quality of grain [8]. A proper supply of nitrogen can promote root development, improve water and nutrient uptake, enhance crop quality, and increase plant tolerance to drought. The beneficial effects of nitrogen, combined with the rising demand for food, have led to the excessive use of nitrogenous fertilizers [9]. Since nitrogen is a nutrient that must be replenished in the soil each year, nitrogenous fertilizers represent the largest share of synthetic fertilizers utilized [10].

The reliable use of nitrogen (N) fertilizer is essential for meeting human food demand; however, excessive use and mismanagement of nitrogen fertilization in agriculture have resulted in elevated levels of nitrous oxide (N_2O) greenhouse gas emissions, air pollution, and groundwater nitrate contamination in many regions worldwide [11]. When over-fertilization occurs alongside improper irrigation practices, it can lead to significant nutrient losses through leaching, contributing to pollution. Groundwater nitrate pollution can disrupt ecological systems and pose risks to human health [12]. To mitigate the risk of nitrate leaching, both fertilizer application and irrigation management practices need to be adjusted [13].

Soil moisture is crucial for the transformation and uptake of plant nutrients by roots. Irrigation and fertilization are interconnected agricultural practices that can optimize yields. Consistently maintaining soil moisture at optimum levels, along with an adequate supply of nitrogen, maximizes crop production. Water is a critical limiting factor for yields in arid and semi-arid regions, which cover about one-third of the Earth. In these areas, effective irrigation programs are essential to achieve maximum efficiency from each unit of irrigation water [14]. The increasing demand for water for industrial, municipal, and environmental purposes has made water scarcity an urgent issue for agriculture. Moreover, the need for sustainable ecosystems exacerbates the water deficit faced by the agricultural sector [15–17]. Given the high demand for both water and nitrogen in buckwheat farming, optimizing these resources is crucial.

However, there are limited studies on the combined effects of water use efficiency and the nutritional properties of grains when both water and nitrogen are applied together in buckwheat. Therefore, this study aims to investigate how varying levels of irrigation and nitrogen fertilization, applied through fertigation, affect water use efficiency, grain yield, and the nutritional properties of buckwheat grown under drip irrigation conditions.

Materials and methods

Field experiments

The experimental material for this study was buckwheat of the Aktaş cultivar. This cultivar is advised for both main season (April–May) and second season (July) sowing, and it is one of only two officially registered buckwheat varieties in Turkey. It has favorable agronomic characteristics, including a plant height of 80–95 cm, white flowers, a 1000-grain weight of 20–29 g, a hectoliter weight of 58–65 kg, a protein content of 11–14%, and the potential for grain yield of 800–1600 kg ha^{-1}. It is also well-suited to the ecological conditions of the study area. The study aimed to investigate the effects of irrigation at 50%, 75%, and 100% of the ETO value, which was calculated from evaporation measurements taken from a Class A evaporation pan. This was combined with four nitrogen doses (0, 30, 60, and 90 kg ha^{-1}) to assess their impact on grain yield and plant characteristics.

Field trials were conducted in Çanakkale, Türkiye (40.1467° N, 26.4086° E), during 2020 and 2021, starting at the end of April. The trials followed a split-plot design with four replications. Each trial plot measured 6 m^2 (1.2 m x 5 m) and consisted of six rows with 20 cm spacing between them. A 2 m gap was left between plots to prevent overlap between fertilizer doses. In the design, the irrigation levels were assigned to the main plots, while nitrogen doses were allocated to the sub-plots.

Table 1 Soil characteristics of the experimental site

Properties	Depth (cm)			
	0–30	**30–60**	**60–90**	**90–120**
Texture	Clay-Loam	Clay-Loam	Sandy-Clay-Loam	Clay-Loam
Saturation (%)	48.93	59.4	40.30	39.90
pH	7.78	8.08	8.11	8.16
EC (dS m^{-1})	0.48	0.435	0.85	1.470
Lime (%)	12.01	18.1	14.8	14.3
Organic Matter (%)	1.49	1.74	1.91	0.82
Phosphorus (kg P_2O_5 ha^{-1})	475.8	396.3	386.2	285.9
Potassium (kg K_2O ha^{-1})	621.7	864.8	-	-
FC (%)	32.8	36.2	35.1	32.5
PWP (%)	19.8	22.6	22.5	19.9
BD (gr cm^{-3})	1.43	1.39	1.46	1.44
AW (mm)	56	57	55	54

EC electrical conductivity, *FC* field capacity, *PWP* permanent wilting point, *BD* bulk density, *AW* available water

Before planting, 80 kg ha^{-1} of pure phosphorus was applied using Triple Super Phosphate fertilizer, and urea (46% N) was used as the nitrogen source. Each nitrogen dose was applied in three stages: one-third at planting, one-third after emergence when the plants reached approximately 20 cm in height, and the remaining third before cluster emergence. Nitrogen was applied through drip irrigation via fertigation, ensuring uniform nutrient delivery in synchronization with crop water requirements. Weed control was carried out throughout the growing season using hoeing and hand-pulling.

Irrigation was initiated when the buckwheat plants reached about 10 cm in height, with six irrigation sessions conducted in total. Harvesting was performed by hand once the grains matured, followed by threshing.

Soil and climate characteristics of experimental sites

Soil samples were collected from four different depth intervals (0–30, 30–60, 60–90, and 90–120 cm), and the analysis results are presented in Table 1. The soil texture was clay-loam except for the 60–90 cm layer, which was sandy-clay-loam. Saturation ranged from 39.90 to 59.40%, while field capacity (32.5–36.2%) and permanent wilting point (19.8–22.6%) showed slight variation. Bulk density was consistent (1.39–1.46 g cm^{-3}), and available water decreased slightly with depth (56–54 mm). The pH values (7.78–8.16) indicated a neutral to slightly alkaline profile, while electrical conductivity (0.48–1.47 dS m^{-1}) and lime content (12.01–18.1%) increased with depth. Organic matter was highest at 60–90 cm (1.91%) and lowest at 90–120 cm (0.82%). Phosphorus content decreased with depth (475.8–285.9 kg P_2O_5 ha^{-1}), and potassium was highest at 30–60 cm (864.8 kg K_2O ha^{-1}).

Climate parameters of the experimental site are shown in Table 2. A comparison of long-term climate data (1937–2019) with the experimental years 2020 and 2021 reveals notable differences in temperature, relative humidity, and precipitation patterns. The mean

Table 2 Temperature, relative humidity, wind speed, rainfall, and evaporation data of the experimental site

Months	Temperature (°C)			Relative Humidity (%)	Wind Speed (m·s^{-1})	Rainfall (mm)	Evaporation (mm)
	Min	**Mean**	**Max**				
Long term (1937–2019)							
May	12.8	17.6	22.6	73.2	3.4	32.0	168.3
June	16.7	22.3	27.8	67.6	3.3	22.4	217.0
July	19.4	25.1	30.7	62.9	3.8	11.7	268.3
August	19.6	25.0	30.6	63.3	4.0	6.5	252.2
September	15.9	20.9	26.4	68.0	3.7	24.2	170.8
Mean/Total	17.1	22.5	27.9	66.8	3.6	72.6	905.8
2020 year							
May	13.5	18.2	23.6	68.9	3.0	54.6	151.9
June	17.8	22.6	28.4	74.0	3.0	38.8	213.7
July	21.7	27.0	32.9	55.3	4.1	0.1	341.2
August	21.6	27.1	33.4	54.2	3.5	3.2	300.1
September	20.6	24.7	29.7	59.6	3.5	9.5	229.9
Mean/Total	18.7	23.7	29.6	63.1	3.4	96.7	1006.9
2021 year							
May	16.0	19.9	25.2	66.6	3.1	57.3	181.7
June	19.5	24.1	29.3	58.3	2.0	57.1	193.0
July	23.5	28.2	33.8	52.0	2.7	2.0	314.5
August	24.1	28.3	33.4	51.1	2.3	0.0	289.8
September	19.1	23.1	27.6	54.0	2.7	8.9	233.7
Mean/Total	20.8	25.1	30.4	57.0	2.5	116.4	979.0

temperature during the experimental years was higher than the long-term average, with 2021 showing the highest mean (25.1 °C) compared to 22.5 °C. Maximum temperatures also increased, reaching 33.8 °C in July 2021. Relative humidity showed a decreasing trend, particularly in 2021, where it dropped to an average of 57%, compared to 66.8% in the long-term data. Rainfall patterns varied; while the total precipitation in 2020 (96.7 mm) was above the long-term average (72.6 mm), it was significantly higher than in 2021 (116.4 mm). Evaporation rates were also elevated in the experimental years, with 2020 reaching 1006.9 mm, indicating higher water loss.

Irrigation systems and treatments

The amount of water applied was determined as 50%, 75%, and 100% of the ET0 value calculated from the evaporation measured weekly using a Class A evaporation pan and was delivered through drip irrigation. The control unit of the system included a pressure regulator, fertilizer tank, sand-gravel filter, mesh filter, manometer, valve, and water meter. The conveyance unit consisted of a main pipe, a manifold (secondary pipe), laterals, and emitters. Irrigation water was supplied by a pump from an artesian well located near the field. The irrigation water was classified as C3S1, with an SAR value of 6.44, an electrical conductivity of 882 µmhos cm^{-1}, and a pH of 7.6. The lateral pipes had a diameter of 16 mm, with drippers having a flow rate of 1.6 L h^{-1} and a spacing of 30 cm. The lateral lines were installed such that one lateral line was allocated to each plant row.

In the first irrigation, the available moisture in the soil was equalized to the field capacity. The amount of water to be supplied to the irrigation subjects was determined using a Class A evaporation container placed in the experimental area. The following equation was used to calculate the amount of irrigation water [18].

$$ETo = E\,pan\;x\;Kpan$$

ETo: Reference crop evapotranspiration, Epan: Pan evaporation, Kpan: Pan coefficient (For the Class-A evaporation pan, Kpan varies between 0.35 and 0.85, it was taken as 0.70).

Crop water consumption

The water budget equation given by James [19] was used to determine crop water consumption as follows:

$$ET = I + R + Cr - Dp - Rf \pm \Delta s$$

ET: crop water consumption (mm), I: irrigation water quantity (mm), R: effective precipitation (mm), Cr: capillary rise (mm), Dp: deep percolation (mm), Rf: surface runoff (mm), Δs: change in soil moisture (mm).

Irrigation water productivity

Irrigation water productivity (IWP) values were calculated with the use of the following equations [20].

$$IWP = \frac{Y}{I}$$

IWP: irrigation water productivity (kg ha mm^{-1}), Y = Yield (kg ha^{-1}), I = amount of irrigation water applied (mm),

Crop water productivity

Crop water productivity (CWP) is defined differently by different researchers [21]. CWP could be defined as the production quantity or value per unit of consumed or diverted water. It is calculated as the ratio of actual yield to the volume of water utilized:

$$CWP = \frac{Y}{ETa}$$

CWP = Crop water productivity (kg m^{-3}), Y = Yield (kg ha^{-1}), ETa = Actual evapotranspiration (m^3 ha^{-1}).

Yield response factor

Stewart model was used to assess the relationships between relative crop water consumption deficit and corresponding yield reduction and yield-response factor (ky) [22]:

$$\left(1 - \frac{Y_a}{Y_m}\right) = k_y \times (1 - \frac{ET_a}{ET_m})$$

Y_a: Actual yield (kg ha^{-1}), Y_m: Maximum yield (kg ha^{-1}), k_y: Yield-response factor, ET_a: Actual crop water consumption (mm), ET_m: Maximum crop water consumption (mm).

Biochemical assays

Harvested buckwheat seed samples were dried, ground (IKA MF 10.1, Staufen, Germany), and made ready for analyses. Samples were preserved at + 4 °C until analysis.

Crude protein

Approximately 1 g of seed sample was taken, and the nitrogen ratio was determined using the Kjeldahl method. The resultant nitrogen value was multiplied by 6.25 (Nx6.25) to obtain the sample crude protein ratio [23].

Crude ash

Approximately 1 g of dry seed sample was ashed in a muffle furnace at 550 °C for 8 h to obtain the crude ash content of the samples.

Resistant, non-resistant, and total starch content
The Megazyme Resistant Starch Assay (catalog number K-RSTAR, Megazyme International Ireland Ltd. Co. Wicklow, Ireland) kit developed in accordance with the AOAC Official Method [24] and AACC [25] Method was used to determine the resistant starch content of 100 mg of each sample.

Amylose and amylopectin content
Amylose and amylopectin fractions of the starch were determined using a Megazyme Amylose/Amylopectin Analysis Kit (K-AMYL, Megazyme International Ireland, Wicklow, Irelan).

Phytic acid
Phytic acid content was detected using a myo-inositol assay kit (K-INOSL, Megazyme Intl, Wicklow, Ireland) in accordance with the instructions of the manufacturer. Approximately 1 g of sample was used in the analysis.

Dietary fiber
Total dietary fiber analysis of the samples will be performed using the Megazyme total dietary fiber kit (AOAC 991.43, AACC 32-07.01, AOAC 985.29 and AACC 32-05.01) and will be calculated as (K-TDFR) and % dietary fiber content.

Crude oil and fatty acid composition
Approximately 3 g of dry sample was placed in a Soxhlet cartridge, dissolved with the help of ether, de-oiled, kept in a drying cabinet at 95 °C for 1 h, cooled in a desiccator, weighed, and calculated [23].

For fatty acid quantification, an initial methylation process was performed in accordance with the Official Method of Analysis 969 – 33 of the AOAC [23]. About 100 µl of the oil sample was placed into potassium hydroxide centrifuge tubes supplemented with 3 ml of hexane and 100 µl of 2 N methanol and centrifuged at 5000 rpm for 5 min. About 1 ml of the supernatant was analyzed in a gas chromatograph (Shimadzo GC/MS, model 2010) equipped with a Supelco HP 88 capillary column (100 m x 0.25 mm ID, 0.2 µm HP 88) and FID (flame ionizing detector) detector. The injection volume was 1 µl and injection temperature was set at 250 °C. The temperature gradient was adjusted as; 1 min at 130 °C, 6.5 °C min^{-1} until 170 °C, 2.75 °C min^{-1} until 215 °C, keep at that temperature for 12 min, 40 °C min^{-1} until 230 °C and keep at that temperature for 5 min. The total analysis duration was 40.89 min. The detector temperature was 280 °C, detector H2 flow rate was 40 ml/min, dry air flow rate was 450 ml min^{-1}, column H2 flow rate was 1.3 ml min^{-1}, and split ratio was 50 L^{-1} [26].

Mineral composition
For mineral contents, approximately 0.25 g buckwheat seed samples were acid-digested in 10 ml of nitric acid + hydrogen peroxide (5:1) acid mixture. Resultant solutions were diluted with distilled water and mineral (P, K, Mg, Ca, Na, S, Fe, Mn, Zn, Ni, Cu and B) readings were performed in a spectrophotometer (Agilent 5800 ICP-OES, USA) by Mertens [27] methods.

Statically analysis
First, variance analysis was performed over the combined years with the use of JMP SAS statistical software [28]. Significant differences were identified using the LSD multiple comparison test.

Results
The impact of irrigation and nitrogen dose interactions on buckwheat yield is presented in Fig. 1. The effects of irrigation regimes, nitrogen doses and I x N interactions on grain yield were found to be statistically significant ($p < 0.01$). While the lowest grain yield was determined as 380 kg ha^{-1} in I50×N0, the highest grain yield was obtained as 2089 kg ha^{-1} in I100×N90 (Fig. 1).

Buckwheat responded well to the increase in nitrogen fertilization and IWP values increased with the increase in nitrogen amount. While the mean IWP in the non-nitrogen applied treatments ranged from 1.43 (I50×N0) to 1.64 (I100×N0) kg ha^{-1} mm^{-1}, it ranged from 2.68 (I50×N30) to 3.97 (I75×N90) kg ha^{-1} mm^{-1} in the fertilized treatments. CWP responded to both irrigation level and nitrogen doses. The lowest mean CWP was 1.13 kg ha^{-1} mm^{-1} in I50×N0 treatment and the highest was 3.39 kg ha^{-1} mm^{-1} in I100×N90 treatment. While the amounts of irrigation water applied to the subjects were 288, 433 and 577 mm in subjects I50, I75 and I100 in 2020, respectively, they were 246, 369 and 492 mm in 2021, respectively. Depending on the amount of irrigation water, ET was calculated as 648 mm in the first year and 586 mm in the second year (Table 3).

The yield response factor (ky) was calculated for all nitrogen doses based on each average value and R^2 values were determined. The value, which was 1.32 in N0 nitrogen dose, became more sensitive in N30 application and was calculated as 1.49. Ky, which was 1.36 in N60 application, was determined as 1.34 in N90 dose, similar to N60. Ky calculated at high R^2 values revealed that buckwheat plant is sensitive to irrigation and nitrogen doses affect this sensitivity (Fig. 2).

The effects of different irrigation and nitrogen doses on the biochemical contents of buckwheat and the average results are presented in Table 4. The effects of irrigation, nitrogen dose, and I × N interaction on crude protein ratio, amylose, condensed tannin, resistant starch, and amylopectin content of buckwheat were found to be

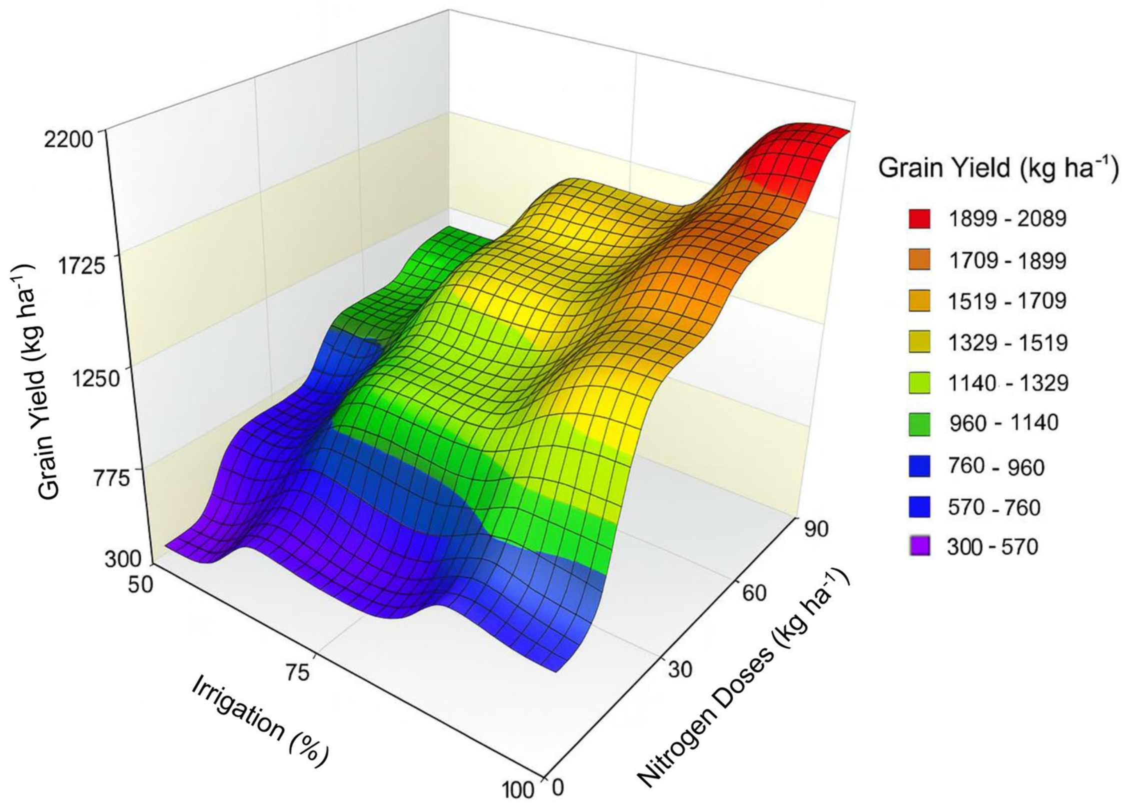

Fig. 1 Grain yield of buckwheat grown under different irrigation levels and nitrogen doses

significant ($p \leq 0.01$), while the I × N interaction was found to be insignificant for other properties.

The results indicate that in terms of I×N interaction the highest crude protein content of buckwheat was observed in the I100×N90 interaction at 14.03%, while the lowest was recorded in the I50×N0 interaction at 9.39%. Similarly, the highest amylose content was found in the I50×N90 interaction at 34.75%, whereas the lowest content occurred in the I75×N0 interaction at 16.61%. The highest condensed tannin content was identified in the I50×N0 interaction at 3.62%, while the lowest was noted in the I50×N90 interaction at 2.22%. Furthermore, the highest resistant starch content was determined in the I100×N90 interaction at 0.53%, whereas the lowest was observed in both the I50×N0 and I50×N30 interactions at 0.07%. The amylopectin content was highest in the I75×N0 treatment at 83.64% and lowest in the I50×N90 interaction at 66.38% (Table 4).

In terms of irrigation levels, the ash content of buckwheat varied between 2.82% and 3.53%, the non-resistant starch content ranged from 38.64 to 55.52%, while total starch content was observed between 38.72% and 55.81%, and phytic acid content ranged from 0.13 to 0.18% with the highest values were obtained from the I100 irrigation level, whereas the lowest were from the I50 level. Regarding nitrogen doses, the ash content varied between 2.35% and 3.93%, non-resistant starch content ranged from 40.81 to 51.51%, total starch content varied between 40.90% and 51.78%, and phytic acid content was found to be between 0.12% and 0.22% with the lowest values were recorded at the N0 dose, while the highest were at the N90 dose. Dietary fiber content, based on irrigation levels, ranged from 5.93% (I100) to 7.61% (I50), while for nitrogen doses, it varied between 5.05% (N90) and 8.65% (N0) (Table 4).

The effects of different irrigation levels and nitrogen doses on the crude oil and fatty acid contents of buckwheat, along with the average results, are presented in Table 5. The effects of irrigation and nitrogen levels on the amounts of crude oil, oleic acid, linoleic acid, arachidonic acid, eicosenoic acid, and trans unsaturated fatty acids (TUSFA) in buckwheat were significant ($p \leq 0.01$), although the interaction between irrigation and nitrogen was considered insignificant in contrast, the effects of all treatments on palmitic acid, stearic acid, linolenic acid, and trans saturated fatty acids (TSFA) were determined to be significant.

In terms of irrigation levels, the highest crude oil content of buckwheat was determined at I100 level at 2.96%, while the lowest was observed at I50 level at

Table 3 Crop water productivity, irrigation water productivity and crop water consumption

IWP 2020					**IWP 2021**					**IWP Mean**				
Irrigation	**Nitrogen Doses**				**Irrigation**	**Nitrogen Doses**				**Irrigation**	**Nitrogen Doses**			
	0	**30**	**60**	**90**		**0**	**30**	**60**	**90**		**0**	**30**	**60**	**90**
50%	1.29	2.43	2.64	2.8	50%	1.58	2.93	4.94	5.7	50%	1.43	2.68	3.79	4.25
75%	1.49	2.08	2.79	3.11	75%	1.64	4.06	4.56	4.82	75%	1.56	3.07	3.68	3.97
100%	1.47	3.13	3.28	3.66	100%	1.64	3.18	3.66	4.2	100%	1.56	3.16	3.47	3.93
CWP 2020					**CWP 2021**					**CWP Mean**				
Irrigation	**Nitrogen Doses**				**Irrigation**	**Nitrogen Doses**				**Irrigation**	**Nitrogen Doses**			
	0	**30**	**60**	**90**		**0**	**30**	**60**	**90**		**0**	**30**	**60**	**90**
50%	1.03	1.88	1.9	1.95	50%	1.22	2.05	3.08	3.7	50%	1.13	1.97	2.49	2.83
75%	1.32	1.82	2.29	2.51	75%	1.42	3.25	3.24	3.67	75%	1.37	2.54	2.77	3.09
100%	1.39	2.96	2.93	3.26	100%	1.53	2.74	3.11	3.52	100%	1.46	2.85	3.02	3.39
ET 2020					**ET 2021**					**ET Mean**				
Irrigation	**Nitrogen Doses**				**Irrigation**	**Nitrogen Doses**				**Irrigation**	**Nitrogen Doses**			
	0	**30**	**60**	**90**		**0**	**30**	**60**	**90**		**0**	**30**	**60**	**90**
50%	360	372	402	413	50%	319	351	395	379	50%	339	362	398	396
75%	487	494	527	535	75%	425	461	519	484	75%	456	477	523	510
100%	610	611	645	648	100%	526	570	578	586	100%	568	591	611	617

2.52%. The oleic acid content varied from 37.32% (I50) to 40.27% (I100), linoleic acid content ranged from 31.23% (I100) to 33.06% (I50), arachidonic acid content varied between 1.98% (I50) and 2.50% (I100), eicosenoic acid content ranged from 2.33% (I50) to 3.12% (I100) and TUSFA ranged from 76.42% (I50) to 77.77% (I100), and. Regarding nitrogen doses, the highest crude oil content was found at N90 dose at 3.29%, while the lowest was recorded at N0 dose at 2.23%. The oleic acid varied between 35.73% (N90) and 42.59% (N0), linoleic acid content varied from 29.22% (N0) to 34.59% (N90), arachidonic acid ranged from 1.66% (N0) to 2.90% (N90), eicosenoic acid content ranged from 2.07% (N0) to 3.19% (N90) and TUSFA ranged from 75.84% (N90) to 78.10% (N0) (Table 5).

According to the I×N interaction, the highest palmitic acid was determined to be 19.47% in the I50×N90 interaction, while the lowest 15.51% in the I75×N0 interaction. The highest stearic acid and linolenic acid contents were determined to be 5.26% and 4.47%, respectively, in the I50×N0 interaction, while the lowest values were recorded at 2.73% and 1.91% in the I100×N90 interaction. The content of TSFA varied between 21.25% (I100×N0) and 25.58% (I50×N90).

The effects of different irrigation levels and nitrogen doses on the mineral content of buckwheat, along with the average results, are presented in Table 6. The effects of irrigation, nitrogen doses, and the interaction between irrigation and nitrogen on the concentrations of Ca, Mg, P, Fe, K, Na, and Cu in buckwheat were significant. However, the impacts of irrigation and nitrogen doses on other properties were significant ($p \leq 0.01$), while the interaction was considered insignificant.

According to the I×N interaction, the highest Ca content in buckwheat was observed in the I50×N0 interaction at 28,470 ppm, while the lowest was recorded in the I100×N90 interaction at 8451 ppm. The highest K content in buckwheat was observed in the I100×N60 interaction at 6051 ppm, while the lowest was recorded in the I50×N0 interaction at 3901 ppm. The highest Mg, P, Fe, Na, and Cu contents were determined in the I100×N90 interaction at 11,226 ppm, 3397 ppm, 71.74 ppm, 746 ppm, and 11.39 ppm, respectively. On the other hand, the lowest Mg, P, Fe, Na, and Cu contents were found in the I50×N0 interaction at 3995 ppm, 2094 ppm, 33.79 ppm, 421 ppm, and 6.77 ppm, respectively (Table 6).

In terms of irrigation levels, the content of B varied between 15.83 and 17.56 ppm, Mn between 14.66 and 28.07 ppm, S between 920 and 1023 ppm, Zn between 31.21 and 37.30 ppm, and Ni between 1.83 and 2.98 ppm with the lowest values were determined at the I50 level, while the highest were found at the I100 level. Regarding nitrogen doses, the content of B ranged from 15.46 ppm (N0) to 17.83 ppm (N90), Mn from 15.93 ppm (N0)

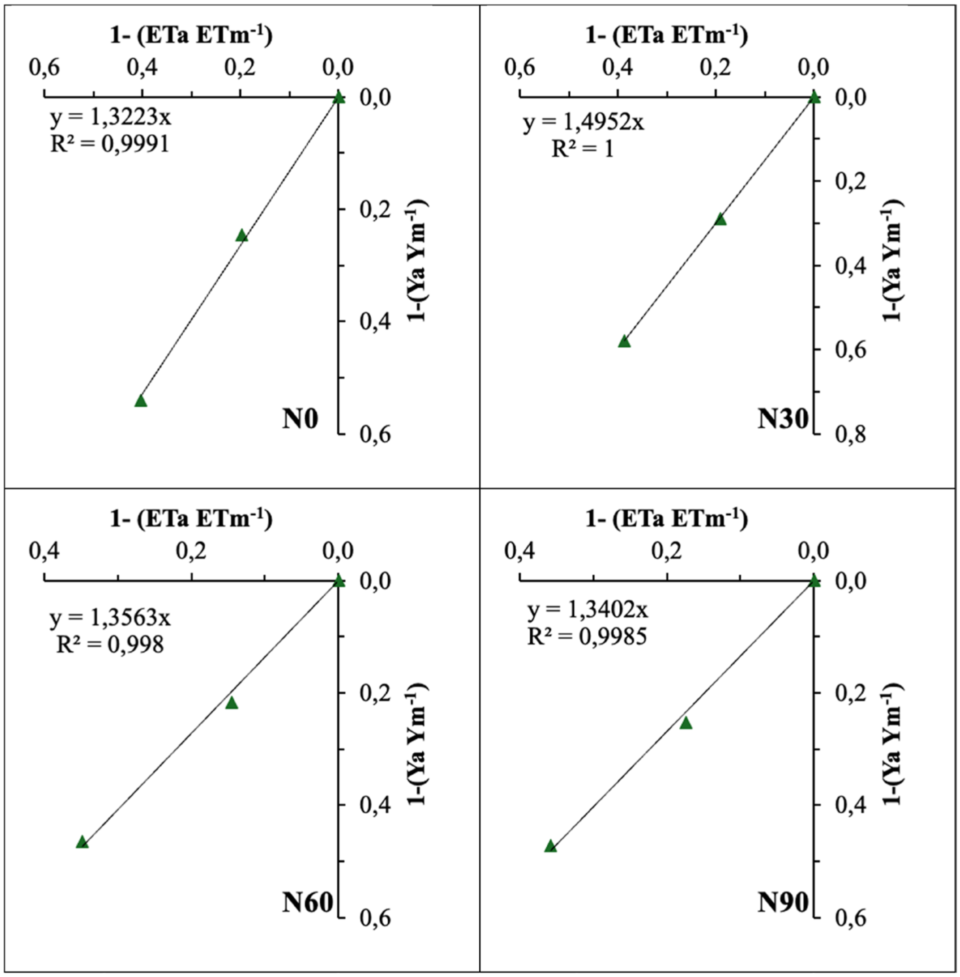

Fig. 2 Yield response factor (ky) values

to 26.13 ppm (N90), S from 794.70 ppm (N0) to 1186.14 ppm (N60), Zn from 30.15 ppm (N0) to 36.71 ppm (N90), and Ni from 1.68 ppm (N0) to 2.94 ppm (N90) (Table 6).

Discussion

This study investigated the effects of water and nitrogen applications on the yield and nutritional properties of buckwheat grain, revealing significant impacts from these applications. Research on buckwheat indicates that environmental conditions, agricultural techniques, plant variety, and climate factors all influence water consumption [29]. Although the water consumption of buckwheat varies with climate characteristics, similar findings were reported by [30]. Crop Water Productivity (CWP) is generally defined as the relationship between biomass produced and the amount of water consumed by the plant (evapotranspiration, ET) (Fink, 2021). CWP is influenced by climate, variety, fertilization, and irrigation practices [31]. It is known that nitrogenous fertilization increases both CWP and Irrigation Water Productivity (IWP) values [32], consistent with the results of this study. These findings are supported by Zhang [33], who reported that moderate nitrogen fertilization delayed senescence and enhanced photosynthetic capacity, resulting in increased buckwheat yield under sufficient irrigation conditions. Our results match those of Guo [34], who showed that mixing rice straw with less inorganic fertilizer helped improve grain filling, starch synthase activity, and yield in common buckwheat. Our study found that using the right amounts of nitrogen and water improved the yield and nutritional quality of the grains, showing that combining nutrient and water management can help sustain buckwheat.

The yield response factor (ky) is a product-specific metric that measures the decline in relative yield as a result of reduced water consumption due to abiotic stress [35]. This factor is also influenced by fertilization practices [36]. In the study, ky was impacted by varying doses of nitrogen fertilization. The interaction between water availability and nitrogen nutrition was found to significantly affect many traits examined in buckwheat. The yield and chemical properties of buckwheat grains were

Table 4 Biochemical properties of buckwheat grain grown under different irrigation levels and nitrogen doses

Crude Protein (%)

Irrigation	Nitrogen Doses (kg ha^{-1})				Mean
	0	30	60	90	
50%	9.39^{f}	10.05^{ef}	11.11^{cd}	11.67^{bc}	10.56^{c}
75%	10.20^{def}	11.06^{cde}	11.53^{bc}	12.38^{b}	11.29^{b}
100%	10.74^{cde}	11.17^{cd}	11.59^{bc}	14.03^{a}	11.88^{a}
Mean	10.11^{d}	10.76^{c}	11.41^{b}	12.70^{a}	

Condense Tannin (%)

Irrigation	Nitrogen Doses (kg ha^{-1})				Mean
	0	30	60	90	
50%	3.62^{a}	2.96^{bc}	2.43^{de}	2.22^{e}	2.81^{b}
75%	3.37^{a}	3.02^{b}	2.93^{bc}	2.71^{cd}	3.01^{a}
100%	3.07^{b}	2.88^{bc}	2.72^{cd}	2.55^{d}	2.80^{b}
Mean	3.35^{a}	2.95^{b}	2.69^{c}	2.49^{d}	

Crude Ash (%)

Irrigation	Nitrogen Doses (kg ha^{-1})				Mean
	0	30	60	90	
50%	1.89	2.6	3.18	3.62	2.82^{c}
75%	2.44	2.84	3.28	3.87	3.11^{b}
100%	2.73	3.38	3.73	4.29	3.53^{a}
Mean	2.35^{d}	2.94^{c}	3.40^{b}	3.93^{a}	

Resistant Starch (%)

Irrigation	Nitrogen Doses (kg ha^{-1})				Mean
	0	30	60	90	
50%	0.07^{d}	0.07^{d}	0.09^{d}	0.11^{cd}	0.08^{c}
75%	0.10^{cd}	0.13^{cd}	0.13^{cd}	0.17^{c}	0.13^{b}
100%	0.11^{cd}	0.13^{cd}	0.36^{b}	0.53^{a}	0.28^{a}
Mean	0.09^{c}	0.11^{c}	0.19^{b}	0.27^{a}	

Non-Resistant Starch (%)

Irrigation	Nitrogen Doses (kg ha^{-1})				Mean
	0	30	60	90	
50%	33.11	37.36	38.78	45.32	38.64^{c}
75%	40	45.55	48.29	49.49	45.83^{b}
100%	49.32	55.88	57.16	59.72	55.52^{a}
Mean	40.81^{c}	46.26^{b}	48.08^{b}	51.51^{a}	

Total Starch (%)

Irrigation	Nitrogen Doses (kg ha^{-1})				Mean
	0	30	60	90	
50%	33.18	37.43	38.86	45.43	38.72^{c}
75%	40.1	45.68	48.42	49.66	45.96^{b}
100%	49.44	56.01	57.53	60.25	55.81^{a}
Mean	40.90^{c}	46.37^{b}	48.27^{b}	51.78^{a}	

Phytic Acid (%)

Irrigation	Nitrogen Doses (kg ha^{-1})				Mean
	0	30	60	90	
50%	0.11	0.11	0.14	0.15	0.13^{b}
75%	0.13	0.13	0.15	0.25	0.17^{a}
100%	0.13	0.16	0.19	0.26	0.18^{a}
Mean	0.12^{c}	0.13b^{c}	0.16^{b}	0.22^{a}	

Total Dietary Fiber (%)

Irrigation	Nitrogen Doses (kg ha^{-1})				Mean
	0	30	60	90	
50%	9.69	7.68	7.26	5.82	7.61^{a}
75%	8.91	7.81	5.72	4.77	6.80^{b}
100%	7.33	6.97	4.85	4.57	5.93^{c}
Mean	8.65^{a}	7.49^{b}	5.94^{c}	5.05^{d}	

Amylose (%)

Irrigation	Nitrogen Doses (kg ha^{-1})				Mean
	0	30	60	90	
50%	26.04^{bcd}	27.68^{bc}	28.45^{b}	34.75^{a}	29.23^{a}
75%	16.61^{gb}	19.52^{fg}	24.70^{de}	28.22^{b}	22.26^{b}
100%	16.97^{g}	22.20^{ef}	24.98^{cde}	26.36^{bcd}	22.63^{b}
Mean	19.87^{d}	23.13^{c}	26.04^{ba}	29.77^{a}	

Amylopectin (%)

Irrigation	Nitrogen Doses (kg ha^{-1})				Mean
	0	30	60	90	
50%	74.26^{cd}	72.37^{d}	71.40^{d}	66.38^{e}	71.10^{b}
75%	83.64^{a}	80.45^{ab}	75.51^{cd}	72.72^{d}	78.08^{a}
100%	83.14^{a}	77.70^{bc}	75.27^{cd}	73.58^{cd}	77.42^{a}
Mean	80.35^{a}	76.84^{b}	74.06^{c}	70.89^{d}	

The differences between the averages of the treatments and the values marked with different letters in the irrigation x nitrogen interactions are statistically significant at the $P < 0.01$ level according to the LSD test

consistent with findings from previous research [37–39]. Among these, Zhang [40] demonstrated that nitrogen application altered starch structure and improved gelatinization, viscosity, and thermal behavior in Tartary buckwheat, supporting our observed increases in resistant starch and protein content. Due to decreased photosynthesis rates and increased stomatal closure caused by water deficiency, plants exhibited shorter heights, limited root development, and reduced biological and grain yields. However, with irrigation, the grain filling period was extended, resulting in an increased number of grains and greater grain weight, ultimately leading to the formation of healthier grains [17].

The extension of the grain-filling period due to sufficient irrigation enhances both yield and quality. Nitrogen fertilization is known to accelerate growth and development in meristem cells located at the base of the internodes. However, this increase is not continuous. In cases of nitrogen deficiency, development time is reduced, leading to shorter plant height and decreased biomass and grain yield [41]. This phenomenon is observed in buckwheat as well as in other plants. The study findings indicate that grain yield increases with higher levels of irrigation and nitrogen application. From an economic standpoint, although the highest grain yield and quality were achieved with the highest nitrogen dose and full irrigation, the input costs associated with such practices are also considerable. Therefore, slightly reduced nitrogen levels (e.g., 60 kg ha^{-1}) combined with 100% irrigation may provide a more economically viable solution by offering near-optimal yield with lower input expenses.

Table 5 Crude oil and fatty acid of buckwheat grain grown under different irrigation levels and nitrogen doses

Crude Oil (%)

Irrigation	Nitrogen Doses (kg ha^{-1})				Mean
	0	30	60	90	
50%	2.13	2.25	2.49	3.23	2.52^{b}
75%	2.03	2.45	2.9	3.01	2.60^{b}
100%	2.53	2.75	2.92	3.65	2.96^{a}
Mean	2.23^{c}	2.48^{bc}	2.77^{b}	3.29^{a}	

Palmitic Acid (C16:0)

Irrigation	Nitrogen Doses (kg ha^{-1})				Mean
	0	30	60	90	
50%	16.26^{cd}	17.04^{bc}	17.52^{b}	19.47^{a}	17.57^{a}
75%	15.51^{d}	16.29^{cd}	17.05^{bc}	17.45^{b}	16.57^{b}
100%	15.55^{d}	16.31^{cd}	16.47^{bcd}	16.94^{bc}	16.32^{b}
Mean	15.78^{c}	16.55^{b}	17.02^{b}	17.95^{a}	

Stearic Acid (C18:0)

Irrigation	Nitrogen Doses (kg ha^{-1})				Mean
	0	30	60	90	
50%	5.26^{a}	4.62^{ab}	3.83^{cd}	3.59^{cde}	4.33^{a}
75%	4.53^{b}	4.05^{bc}	3.32^{def}	3.03^{ef}	3.73^{b}
100%	4.00^{bc}	4.00^{bc}	3.55^{cde}	2.73^{fa}	3.57^{b}
Mean	4.60^{a}	4.22^{b}	3.57^{c}	3.12^{d}	

Oleic Acid (C18:1)

Irrigation	Nitrogen Doses (kg ha^{-1})				Mean
	0	30	60	90	
50%	40.32	37.82	37.20	33.94	37.32^{b}
75%	42.4	39.39	37.90	36.10	38.95^{b}
100%	45.05	40.9	37.98	37.15	40.27^{a}
Mean	42.59^{a}	39.37^{b}	37.69^{b}	35.73^{c}	

Linoleic Acid (C18:2)

Irrigation	Nitrogen Doses (kg ha^{-1})				Mean
	0	30	60	90	
50%	30.2	32.92	33.97	35.15	33.06^{a}
75%	29.87	31.88	33.68	34.4	32.46^{a}
100%	27.59	30.38	32.73	34.21	31.23^{b}
Mean	29.22^{c}	31.73^{b}	33.46^{a}	34.59^{a}	

Linolenic Acid (C18:3)

Irrigation	Nitrogen Doses (kg ha^{-1})				Mean
	0	30	60	90	
50%	4.47^{a}	4.00^{abc}	3.29^{cd}	3.08^{d}	3.71^{a}
75%	4.16^{ab}	3.92^{abc}	3.33^{cd}	2.02^{e}	3.36^{b}
100%	4.05^{abc}	3.58^{bcd}	3.07^{d}	1.91^{e}	3.15^{b}
Mean	4.22^{a}	3.83^{b}	3.23^{c}	2.34^{d}	

Arachidonic Acid (C20:0)

Irrigation	Nitrogen Doses (kg ha^{-1})				Mean
	0	30	60	90	
50%	1.61	1.84	1.97	2.52	1.98^{b}
75%	1.67	1.92	2.41	2.99	2.25^{ab}
100%	1.69	2.29	2.82	3.19	2.50^{a}
Mean	1.66^{c}	2.01^{c}	2.40^{b}	2.90^{a}	

Eicosaenoic Acid (C20:1)

Irrigation	Nitrogen Doses (kg ha^{-1})				Mean
	0	30	60	90	
50%	1.97	2.3	2.55	2.51	2.33^{c}
75%	2.12	2.7	2.75	3.18	2.68^{b}
100%	2.13	3.03	3.46	3.88	3.12^{a}
Mean	2.07^{c}	2.68^{b}	2.92^{ab}	3.19^{a}	

TUSFA

Irrigation	Nitrogen Doses (kg ha^{-1})				Mean
	0	30	60	90	
50%	76.95	77.05	77	74.68	76.42^{b}
75%	78.55	77.89	77.66	75.7	77.45^{a}
100%	78.81	77.88	77.22	77.15	77.77^{a}
Mean	78.10^{a}	77.61^{a}	77.30^{a}	75.84^{b}	

TSFA

Irrigation	Nitrogen Doses (kg ha^{-1})				Mean
	0	30	60	90	
50%	23.13^{bc}	23.50^{b}	23.33^{b}	25.58^{a}	23.88^{a}
75%	21.71^{cd}	22.25^{bcd}	22.81^{bc}	23.37^{b}	22.54^{b}
100%	21.25^{d}	22.60^{bcd}	22.85^{bc}	22.86^{bc}	22.39^{b}
Mean	22.03^{c}	22.78^{b}	23.00^{b}	23.94^{a}	

The differences between the averages of the treatments and the values marked with different letters in the irrigation x nitrogen interactions are statistically significant at the $P < 0.01$ level according to the LSD test

Under stress conditions such as water restrictions and nutrient deficiencies, changes in assimilate transport can alter metabolic and enzyme activities, which in turn affect the chemical composition of the seeds. When nutrients accumulated in the leaves cannot be transported to the grain due to water limitations, there is a reduction in the protein and starch content of the grains [42]. In addition to optimizing water and nitrogen levels, nitrogen losses can also be reduced through the use of controlled-release fertilizers, split nitrogen applications, and nitrification inhibitors, which help minimize leaching and volatilization under varying moisture conditions. Water stress leads to decreased carbohydrate, protein, and ash content [17]. Similar studies conducted on sorghum [43], chickpeas [17], wheat [44], and corn [16] have shown that irrigation increases the ratios of protein and starch.

Resistant starch is a component of total starch that cannot be broken down by enzymes in the human digestive system. Instead, it is fermented by bacteria in the large intestine. Resistant starch plays a significant role in preventing various diseases [45]. In the current study, resistant starch content increased significantly under full irrigation and the highest nitrogen dose (I100×N90), reaching 0.53%. In contrast, the lowest content (0.07%) was observed in treatments with limited irrigation and no or low nitrogen application (I50×N0 and I50×N30). These findings are consistent with previous research indicating that optimal water and nitrogen availability enhance starch synthesis and the accumulation of resistant starch in cereal grains. Research indicates that

Table 6 Mineral content of buckwheat grain grown under different irrigation levels and nitrogen doses

Ca (ppm)

Irrigation	Nitrogen Doses (kg ha^{-1}) 0	30	60	90	Mean
50%	28470^{a}	26061^{ab}	16961de	14997^{e}	21623^{a}
75%	26532^{ab}	24552^{b}	18631^{cd}	17088de	21701^{a}
100%	20961^{c}	19581^{cd}	12065^{f}	8451^{g}	15265^{b}
Mean	25321^{a}	23398^{b}	15886^{c}	13512^{d}	

K (ppm)

Irrigation	Nitrogen Doses (kg ha^{-1}) 0	30	60	90	Mean
50%	3901^{e}	4493^{cde}	5373^{b}	4948^{bcd}	4679^{b}
75%	4019^{e}	4415de	5017^{bc}	5102^{b}	4638^{b}
100%	4087^{e}	4802^{bcd}	6051^{a}	6046^{a}	5247^{a}
Mean	4002^{c}	4570^{b}	5481^{a}	5365^{a}	

Mg (ppm)

Irrigation	Nitrogen Doses (kg ha^{-1}) 0	30	60	90	Mean
50%	3995^{h}	6349^{fg}	7127^{ef}	8269^{cd}	6435^{c}
75%	5906^{g}	7734de	8770^{bc}	9313^{b}	7931^{b}
100%	5915^{g}	8458^{bcd}	9294^{b}	11226^{a}	8722^{a}
Mean	5271^{d}	7514^{c}	8397^{b}	9603^{a}	

Na (ppm)

Irrigation	Nitrogen Doses (kg ha^{-1}) 0	30	60	90	Mean
50%	421^{f}	525de	595^{cd}	563de	526^{c}
75%	495^{ef}	533de	600^{cd}	644^{bc}	568^{b}
100%	539de	571^{cde}	697^{ab}	746^{a}	638^{a}
Mean	485^{c}	543^{b}	631^{a}	651^{a}	

P (ppm)

Irrigation	Nitrogen Doses (kg ha^{-1}) 0	30	60	90	Mean
50%	2094^{g}	2359^{fg}	2439^{ef}	2534^{def}	2356^{c}
75%	2472^{ef}	2626^{cdef}	2853^{bc}	2820^{bc}	2693^{b}
100%	2669^{cde}	2771^{bcd}	3015^{b}	3397^{a}	2963^{a}
Mean	2411^{d}	2585^{c}	2769^{b}	2917^{a}	

S (ppm)

Irrigation	Nitrogen Doses (kg ha^{-1}) 0	30	60	90	Mean
50%	710	876	1190	904	920^{b}
75%	802	988	1159	934	971^{ab}
100%	872	1084	1210	925	1023^{a}
Mean	795^{c}	983^{b}	1186^{a}	921^{b}	

B (ppm)

Irrigation	Nitrogen Doses (kg ha^{-1}) 0	30	60	90	Mean
50%	14.73	15.64	16.42	16.55	15.83^{c}
75%	15.46	15.68	17.10	17.61	16.46^{b}
100%	16.18	17.03	17.70	19.32	17.56^{a}
Mean	15.46^{c}	16.12^{c}	17.07^{b}	17.83^{a}	

Cu (ppm)

Irrigation	Nitrogen Doses (kg ha^{-1}) 0	30	60	90	Mean
50%	6.77^{f}	7.39^{ef}	8.87^{bcde}	7.85^{ef}	7.72^{b}
75%	7.88^{ef}	8.20^{def}	9.58^{bcd}	10.11^{ab}	8.94^{a}
100%	7.93^{ef}	8.40^{cde}	9.92^{abc}	11.39^{a}	9.41^{a}
Mean	7.53^{b}	8.00^{b}	9.46^{a}	9.78^{a}	

Fe (ppm)

Irrigation	Nitrogen Doses (kg ha^{-1}) 0	30	60	90	Mean
50%	33.79^{d}	36.53^{d}	37.44^{d}	51.17^{bc}	39.73^{c}
75%	40.27^{cd}	44.63^{cd}	63.56^{ab}	62.89^{ab}	52.84^{b}
100%	46.23^{cd}	59.94^{ab}	70.25^{a}	71.74^{a}	62.04^{a}
Mean	40.10^{c}	47.03^{b}	57.08^{a}	61.93^{a}	

Zn (ppm)

Irrigation	Nitrogen Doses (kg ha^{-1}) 0	30	60	90	Mean
50%	28.74	30.69	32.92	32.51	31.21^{c}
75%	29.16	35.66	36.85	37.40	34.77^{b}
100%	32.55	37.80	38.64	40.22	37.30^{a}
Mean	30.15^{b}	34.72^{a}	36.13^{a}	36.71^{a}	

Mn (ppm)

Irrigation	Nitrogen Doses (kg ha^{-1}) 0	30	60	90	Mean
50%	9.15	14.57	15.40	19.52	14.66^{c}
75%	17.12	19.26	24.84	26.49	21.93^{b}
100%	21.52	28.13	30.24	32.38	28.07^{a}
Mean	15.93^{d}	20.65^{c}	23.50^{b}	26.13^{a}	

Ni (ppm)

Irrigation	Nitrogen Doses (kg ha^{-1}) 0	30	60	90	Mean
50%	1.09	1.87	2.14	2.22	1.83^{c}
75%	1.90	2.62	3.00	3.11	2.66^{b}
100%	2.05	3.02	3.37	3.47	2.98^{a}
Mean	1.68^{c}	2.50^{b}	2.84^{a}	2.94^{a}	

The differences between the averages of the treatments and the values marked with different letters in the irrigation x nitrogen interactions are statistically significant at the $P < 0.01$ level according to the LSD test

water restriction reduces the levels of total starch, amylose, and the amylose/amylopectin ratio in barley [46]. Conversely, studies have shown that increasing irrigation leads to a higher ratio of resistant starch [16]. The amount of phytic acid in cereal grains is influenced by several factors, including genetic structure, planting time, soil properties, irrigation, fertilization, climate conditions, and their interactions [47]. Specifically, higher levels of irrigation have been linked to increased phytic acid content in grains [48]. Water stress tends to increase the fiber content of grains by enhancing cell wall components, but it also results in decreased levels of protein, oil, and starch [17]. Nitrogen obtained from nitrogenous fertilizers is essential for chlorophyll and protein synthesis. It has been observed that nitrogen fertilization boosts both protein and starch levels in plants [49]. Additionally, increasing the application of nitrogen significantly raises ash content due to enhanced carbon assimilation [50]. In various studies, higher nitrogen doses led to increases in protein, starch, and ash ratios. Specifically, it was found that as nitrogen fertilization levels increased, the amylose content rose while the amylopectin ratio decreased in rice [51], wheat [44], and maize [16]. However, Ovando-Martínez et al. [52] reported that water limitation increased the amylose content in beans. Moreover, nitrogen fertilization enhances grain photosynthesis and promotes starch accumulation during grain filling, thereby supporting overall grain growth and raising the starch ratio [37, 53]. In contrast, it has been shown that the levels of total phosphorus and phytic acid in grains tend to decrease as the nitrogen ratio increases [54].

In the study, an increase in oil content in the grain is observed with rising doses of water and nitrogen. Research has shown that irrigation enhances the oil content in various crops, including popcorn [55], milk thistle [56], soybean [57], and dent corn [26]. However, irrigation does not affect oil content in canola [58] and actually reduces it in rapeseed [59]. This indicates that plants respond differently to irrigation regarding oil content. Proper nitrogen application significantly boosts the levels of fatty acids, total unsaturated fatty acids, linoleic acid, and oleic acid [60]. Moderate nitrogen levels can enhance oil synthesis, while excessive nitrogen can suppress lipid synthesis. Ashraf et al. [61] found that nitrogen fertilization did not affect the level of linoleic acid in black cumin oil. Therefore, the impact of nitrogen applications on oil content can be complex.

Additionally, a shortage of irrigation water may negatively influence oil synthesis, resulting in decreased oil content in the grain [26]. The levels of irrigation water applied are known to significantly affect the oleic acid content [62]. Water stress is known to limit root development, which in turn reduces the uptake of essential nutrients from the soil. A lack of water can hinder the absorption of mineral elements by plants, leading to decreased ash and mineral content in grains [63]. Notably, significant increases in ash content have been observed with higher doses of nitrogen fertilizer in buckwheat [37]. Under drought conditions, the roots' nutrient uptake diminishes, and the transport of nutrients is restricted by reduced transpiration rates from roots to shoots, as well as impaired active transport processes [64]. Consequently, the absorption of various elements decreases with diminishing water availability in the soil. Additionally, water stress impacts the uptake rates of soil elements to varying degrees [65]. Iron (Fe) and zinc (Zn), which are common minerals in the human diet [66], are especially vital in arid and semi-arid regions due to their high sensitivity to irrigation conditions [65]. Kayodé et al. [67] found that the contents of Fe and Zn are more influenced by environmental factors than by genetic traits. Moreover, drought stress leads to a reduction in total phosphorus (P) accumulation in plants, negatively affecting growth and development [68].

Nitrogen fertilization enhances the contents of nitrogen (N), potassium (K), sulfur (S), and phosphorus (P) in cereal grains [69]. The requirement and metabolism of sulfur in plants are closely linked to the amount of nitrogen available, demonstrating a positive and significant relationship between the two [70]. Additionally, nitrogen fertilization improves the uptake of iron (Fe) and zinc (Zn) from the soil, thereby increasing their concentrations in cereal grains [71]. Calcium (Ca) also plays a protective role against stress conditions and is crucial for various structural and physiological processes in plants, including cell wall integrity, membrane structure, cell division, and photomorphogenesis [72]. Its concentration tends to rise under stressful conditions. In this study, it was observed that both increased water stress and nitrogen deficiency led to higher calcium accumulation in buckwheat grains.

Conclusion

This study clearly demonstrated that varying nitrogen doses and irrigation levels applied through fertigation had significant impacts on water use efficiency, yield, and grain nutritional quality in buckwheat. Irrigation and fertilization play a critical role in the structure of the grain. This can affect the processing properties and nutritional value of the grain. Optimal management of irrigation levels and nitrogen doses is critical to maximize the nutritional quality of the grain. While inadequate irrigation puts the plant under stress and reduces protein, mineral, and oil content, nitrogen deficiency similarly negatively affects the biochemical composition of buckwheat grain. Achieving a delicate balance, especially in starch structure, will ensure that agricultural products are more functional and nutritious. At the end of the study, 100% irrigation level and 90 kg ha^{-1} nitrogen doses are recommended for optimum yield and quality in buckwheat cultivation. However, it is essential to consider the economic returns when applying high levels of nitrogen and irrigation. While 90 kg ha^{-1} nitrogen provided the highest yield, 60 kg ha^{-1} might be a more cost-effective choice for many growers. Furthermore, to reduce nitrogen loss and minimize environmental risks, the adoption of techniques such as split nitrogen application, controlled-release fertilizers, and nitrification inhibitors is strongly recommended. However, considering economic and environmental effects, optimum irrigation nitrogen doses should be determined according to regional climate and soil conditions.

Acknowledgements
We are grateful for the support of the Scientific Research Project Unit of Erciyes University (Turkiye).

Authors' contributions

Beyza Ciftci: Data curation, Formal analysis Writing-original draft and editing. Sevim Akcura: Methodology, Field Experiment, Data curation, Formal analysis. İhsan Serkan Varol: Data curation, Formal analysis, Writing-original draft. Yusuf Murat Kardes: Data curation, Formal analysis Writing-original draft. Ismail Tas: Field Experiment, Data curation, Writing-original draft. Mahmut Kaplan: Funding acquisition, Data curation, Methodology, Writing-original draft, Writing-review and editing.

Funding

The project was supported by the Scientific Research Project Unit of Erciyes University (FBA-2023-12412).

Data availability

The datasets analyzed during the current study are available from the corresponding author on reasonable request. (mahmutkaplan5@hotmail.com M. Kaplan).

Declarations

Ethics approval and consent to participate

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 24 April 2025 / Accepted: 18 June 2025
Published online: 22 July 2025

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