

Water-Nitrogen Trade-Offs Shape Quinoa Productivity, Resource Use Efficiency, Water Productivity, and Profitability in Semi-Arid Conditions

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Abstract

Quinoa (*Chenopodium quinoa* Willd.) is increasingly recognized for its nutritional value and tolerance to abiotic stress, offering potential to diversify cropping systems in water-scarce regions. However, site-specific irrigation and nitrogen (N) management recommendations for the only officially released quinoa varieties in Pakistan remain undefined. Therefore, a three-year consecutive field study (2021–2024) was conducted in Pakistan, using a split-plot randomized complete block design along with four irrigation regimes (one to four irrigation events at 35, 75, 105, and 125 days after sowing) as main plots and four nitrogen rates (0, 40, 80, and 120 kg N ha⁻¹) as subplots. All measured traits were significantly affected by irrigation × nitrogen interaction ($P \leq 0.01$). Three irrigation events combined with 120 kg N ha⁻¹ (I₃N₄) produced the highest grain yield (1017–1304 kg ha⁻¹) and the highest benefit-cost ratio (BCR) in two of three years (up to 4.11). In contrast, four irrigation events with 40 kg N ha⁻¹ (I₄N₂) achieved the highest values across all three nitrogen use efficiency (NUE) indices, and two irrigation events with 120 kg N ha⁻¹ (I₂N₄) achieved the highest water use efficiency (WUE) (up to 1.96 kg m⁻³). Even the best-yielding treatment reached only 32–41% of the UAF-Q7 yield potential, which may be due to agronomic practices such as early sowing, low soil organic matter, and available phosphorus, rather than to water or nitrogen supply. The results demonstrate distinct water-nitrogen management optima depending on whether production, profitability, nitrogen efficiency, or water-use efficiency is prioritized. The persistent gap between observed yield and the reported yield potential of UAF-Q7 indicates that soil fertility and other agronomic constraints require attention alongside irrigation and nitrogen management.

1. Introduction

Environmental changes, including climate change, drought, salinity, land degradation, and freshwater scarcity, are increasingly threatening agricultural productivity and global food security (Mirzabaev et al., 2023; Yang et al., 2024). These challenges are further exacerbated by rapid population growth, with the global population projected to approach 10 billion by 2050 (Ritchie & Rodés-Guirao, 2024), alongside ongoing arable land degradation and increasing freshwater scarcity (Hussain et al., 2025). Conventional staple crops such as wheat, rice, and maize are increasingly vulnerable to heat stress, drought, and soil salinity, raising concerns about their long-term capacity to meet nutritional demand (Lamaoui et al., 2018). These pressures have intensified interest in stress-tolerant, nutritionally dense alternative crops suited to marginal environments.

Quinoa (*Chenopodium quinoa* Willd.), a pseudocereal native to the Andean region of South America (González et al., 2015), has emerged as a strong candidate, due to its tolerance to drought, salinity, and frost, combined with high nutritional value and broad agro-ecological adaptability (Alandia et al., 2020; Jacobsen et al., 2005; Mousa et al., 2025). All major plant parts, grains, leaves, and inflorescences, are edible, and the crop is notably rich in protein (10–18%), fats (4.1–8.8%), carbohydrates, minerals, vitamins, and all essential amino acids (Bhargava et al., 2007; Mota et al., 2016; Pilco-Quesada et al., 2020). The grain is also gluten-free and has been successfully incorporated into wheat-flour substitutes for bread and other food processing applications (Melini & Melini, 2021; Peñas et al., 2014; Stikic et al., 2012). Due to its nutritional values and agronomic favorability, quinoa cultivation can contribute significantly to addressing global food security challenges.

Quinoa is cultivated across multiple continents, with major producing countries including Bolivia, Brazil, Chile, Colombia, Ecuador, and Peru (Alandia et al., 2020; Bazile et al., 2016; Maughan et al., 2007). Its phenological development is sensitive to both temperature and photoperiod, which underlies its broad adaptability across latitudes (Bertero, 2001, 2003; Jacobsen & Stølen, 1993a; Salehi et al., 2019). Quinoa anthesis occurs within 7–50 days, bud initiation approximately 40–89 days after sowing, and maturity 66–135 days after anthesis (Bertero et al., 1999a; Curti et al., 2016; Jacobsen & Stølen, 1993b).

Water and nitrogen availability are primary constraints on agricultural production, especially in semi-arid regions (Ahmad et al., 2025; Roman et al., 2023; Wahab et al., 2024). Despite quinoa's potential, key challenges that limit widespread adoption include the lack of high-yielding, adapted genotypes and insufficient knowledge of optimal water and nutrient management practices (Garcia et al., 2015; Noulas et al., 2017; Taaime, Rafik, et al., 2023). Nitrogen (N) is a primary macronutrient that fundamentally governs quinoa growth, biomass accumulation, and reproductive development (Deng et al., 2023a). Under Mediterranean conditions, nitrogen application at 150 kg ha^{-1} maximized quinoa grain yield at 2.95 t ha^{-1} while achieving a crude protein content of 16%, identifying this rate as optimal for both productivity and nutritional quality (Geren, 2015). Similarly, the increased N fertilization (up to 160 kg ha^{-1}) enhanced the quinoa yield ($101\text{--}770 \text{ kg ha}^{-1}$) and protein content (14.8–17.1%) but reduced nitrogen use efficiency (NUE) from 5.52 to 4.31, indicating trade-offs between yield and NUE at higher N rates (Almadini, Badran, et al., 2019). Moreover, the increased N concentration at $\geq 210\text{--}375 \text{ kg ha}^{-1}$ declined the NUE due to excessive N losses (Bahrami et al., 2022a; Deng et al., 2023b; Li et al., 2024, 2025a). Under saline stress conditions, N application has additionally been shown to improve yield components and water use efficiency (WUE), highlighting its critical role in stress-prone production environments (Alizadeh-Zoaj et al., 2023; Hussain et al., 2020; Mahmoud & Sallam, 2017). Collectively, these findings underscore that balanced N fertilization is essential for optimizing quinoa yield, NUE, and overall resource use efficiency (Choukr-Allah et al., 2016; Mengen et al., 2026).

Quinoa exhibits strong inherent resilience to abiotic stresses, particularly drought and salinity (Ruiz et al., 2016). Research indicates that water availability and irrigation management substantially affect quinoa development, including physiological performance (Al-Naggar et al., 2017b; Cocozza et al., 2013; Jacobsen et al., 2009), morphological attributes (Issa Ali et al., 2019; Razzaghi, Ahmadi, et al., 2012), and seed chemical composition (Ain et al., 2023; Nowak et al., 2016; Pulvento et al., 2012). The impact of drought stress varies with drought intensity and plant developmental stage. The timing of drought stress determines its impact on quinoa productivity: early-stage drought enhances water use efficiency (Xu et al., 2025), whereas drought during pre-flowering through dough stages or flowering and seed-filling significantly reduces yield (Geerts et al., 2008; González et al., 2009; Jensen et al., 2000). Drying and rewetting cycles are frequent in semi-arid regions, and flowering is the most vulnerable period for quinoa (He & Dijkstra, 2014). Quinoa maintains water balance by regulating water uptake relative to transpiration, preventing dehydration during soil water deficits. The plant improves water absorption by accumulating cellular solutes, thereby reducing root water potential and facilitating water movement (Alandia et al., 2016). Similarly, in another study, quinoa maintained acceptable seed yield under severe water deficit irrigation, with a 70% reduction in water supply causing only a 36% yield loss and a 12% improvement in water productivity under shallow saline groundwater conditions (Talebnejad & Sepaskhah, 2015). Recent experimental studies indicates that moderate irrigation combined with balanced nitrogen fertilization is essential for optimizing quinoa yield, nitrogen use efficiency, and

environmental sustainability in water-limited regions (Bahrami et al., 2022a; Li et al., 2025b; Pradhan et al., 2025).

Given its nutritional value and adaptability, quinoa has considerable potential to contribute to food security, particularly in water-limited regions. However, optimizing the interaction between N fertilization and irrigation remains essential to maximizing yield, NUE, and economic returns. There is limited evidence on the combined effects of irrigation levels and N management on quinoa under semi-arid South Asian conditions. Therefore, this study was conducted to determine the optimal N rates for successful, sustainable quinoa production under drought stress in semi-arid conditions. The specific objectives of the study were to; (1) quantify the main and interactive effects of irrigation frequency (1–4 events) and N rate (0–120 kg N ha⁻¹) on phenology, biomass accumulation, yield components, and grain yield of quinoa across three consecutive growing seasons; (2) determine the responses of water use efficiency (WUE), nitrogen use efficiency (NUE) indices (agronomic, physiological, and recovery efficiencies), and benefit–cost ratio (BCR) to contrasting irrigation × N management strategies; and (3) identify the optimal irrigation × N treatment combination that simultaneously maximizes grain yield, WUE, NUE, and economic profitability, and evaluate the magnitude and key drivers of the yield gap between observed and attainable yield of UAF-Q7 under semi-arid conditions.

2. Materials and methods

2.1 Experimental Site and Soil Characterization

Field experiments were conducted over three consecutive winter cropping seasons (2021-22, 2022-23, and 2023-24) at the research farm of the Agronomy Institute, Bahauddin Zakariya University, Multan, Pakistan (30°11'N, 71°28'E). The experimental site is characterized by an irrigated semi-arid climate, with a mean annual precipitation of 175 mm and a mean annual temperature of 25.6°C during the winter season of 2021–2024 (Data collected from the weather station of Central Cotton Research Institute, Multan). Monthly minimum and maximum temperatures and cumulative rainfall recorded during each growing season are presented in Figs. 1 and 2.

Prior to the initiation of the experiment, composite soil samples were collected from two depth increments (0–15 cm and 15–30 cm) to characterize the baseline physicochemical and fertility status of the experimental site. The soil was loam in texture with the following properties: organic matter 0.51%, available phosphorus 7.81 mg kg⁻¹, total available nitrogen 0.015%, exchangeable potassium 69 mg kg⁻¹, pH 8.4, electrical conductivity 1.33 dSm⁻¹, and saturation percentage 36%.

2.2 Experimental Design and Treatments

A split-plot arrangement within a randomized complete block design (RCBD) was employed with three replications. Irrigation regimes were assigned to main plots and nitrogen application rates to subplots, with individual subplot dimensions of 4 m × 3 m (gross plot area: 12 m²). The experiment was conducted as a two-factor study across three seasons, with year included as a factor in the statistical model to account for seasonal variation in climatic conditions.

Four irrigation levels constituted the main plot treatments: I_1 = one irrigation event (35 day after sowing (DAS)), I_2 = two irrigation events (35 and 75 DAS), I_3 = three irrigation events (35, 75, and 105 DAS), and I_4 = four irrigation events (35, 75, 105, and 125 DAS). Each irrigation event delivered approximately (251.1 mm ha⁻¹) of water per application, resulting in total seasonal water inputs of approximately (251.1 mm ha⁻¹, 502.1 mm ha⁻¹, 753.2 mm ha⁻¹ and 1004 mm ha⁻¹) mm for I_1 through I_4 , respectively. Subplot treatments comprised four N application rates: N_1 = 0, N_2 = 40, N_3 = 80, and N_4 = 120 kg ha⁻¹. The quinoa variety UAF-Q7 was procured from Muhammad Nawaz Shareef University of Agriculture (MNS-UA), Multan, Pakistan, and used consistently across all three experimental seasons.

2.3 Crop Establishment and Agronomic Management

The experimental field was pre-irrigated approximately one week prior to sowing to ensure adequate soil moisture for uniform germination. Seedbed preparation consisted of two deep ploughings followed by planking to achieve a fine, firm, and uniform tilth. Quinoa seeds were sown on 28 October in each of the three experimental seasons using a seed drill at a seed rate of 5 kg ha⁻¹, with 60 cm row-to-row spacing and 15 cm intra-row plant spacing. Following crop emergence, gap filling and thinning were performed to establish and maintain the target plant population throughout the growing season.

Phosphorus (P) and potassium (K) were applied as basal doses at rates of 50 kg ha⁻¹ P₂O₅ and 50 kg ha⁻¹ K₂O using diammonium phosphate (DAP) and sulfate of potash (SOP), respectively, incorporated into the soil at the time of final seedbed preparation. N was applied as urea (46% N) in two equal split applications: the first at sowing and the second at 35 DAS at first irrigation, across all treatment combinations. Weed control was performed manually through periodic hand hoeing at 20 and 45 DAS to prevent weed competition during the critical early growth period. At physiological maturity, plants were harvested manually, excluding one border row on each side. Harvested material was bundled and dried under ambient field conditions for 72 hours, then weight after threshing for yield determination.

2.4 Irrigation Water Measurement and Application

Irrigation water was delivered and quantified using a calibrated cutthroat flume (90 cm × 20 cm). Duration of each irrigation event required to deliver the target water volume was determined using following equation:

$$T = \frac{A \times d}{Q}$$

1

where T is the total duration of water application (h), A is irrigated plot area (m²), d is the target irrigation depth (m), and Q is the volumetric flow rate (m³ s⁻¹). The actual volume of water delivered at each irrigation event was recorded and used in all subsequent water use efficiency calculations. The rainfall during the crop period is excluded.

2.5 Grain yield and Water Use Efficiency

Grain yield-based WUE was calculated following (Bouman et al., 2007) as:

$$WUE = \frac{GY}{TWA}$$

2

Where GY is the grain yield (kg ha^{-1}), and TWA is total water applied (mm).

2.6 Nitrogen Use Efficiency

Three complementary indices of NUE were calculated following the methodology of Srivastava et al. (2018). These factors were computed to explore the performance of the best agricultural management practices (Mon et al., 2016). Agronomic nitrogen use efficiency (ANUE; $\text{kg grain kg}^{-1} \text{ N}$) quantifies yield gain per unit of nitrogen applied:

$$ANUE = \frac{(GY_N - GY_0)}{N_r}$$

3

Where GY_N is grain yield under a given nitrogen treatment (kg ha^{-1}), GY_0 is grain yield of the zero-nitrogen control plot within the same irrigation level (kg ha^{-1}), and N_r is nitrogen application rate (kg ha^{-1}).

Economic nitrogen use efficiency (ENUE; currency $\text{kg}^{-1} \text{ N}$) quantifies the monetary return per unit cost of nitrogen applied:

$$ENUE = \frac{(GY_N - GY_0)}{N_{cost}}$$

4

Where GY_N and GY_0 are the gross monetary values of grain yield ($\text{\$ ha}^{-1}$) under the nitrogen-treated and zero-nitrogen control plots, respectively, and N_{cost} is the monetary cost of nitrogen applied ($\text{\$ ha}^{-1}$).

Partial factor productivity of nitrogen (PFP_N; $\text{kg grain kg}^{-1} \text{ N}$) quantifies total grain production per unit of nitrogen supplied:

$$PFPN = \frac{GY}{N_r}$$

5

Where GY is total grain yield (kg ha^{-1}), and N_r is the nitrogen application rate (kg ha^{-1}).

2.7 Economic Analysis

The economic performance of each treatment combination was evaluated by calculating total expenditure (TE), gross income (GI), net income (NI), and benefit-cost ratio (BCR) following the Perrin et al. (1976) budget

methodology. Total expenditure encompassed all variable production costs from land preparation through to harvest, including tillage, seed, fertilizer inputs (urea, DAP, SOP), irrigation labor, weed management, and harvesting costs (Yousafi et al., 2020).

$$\text{Net Income (NI)} = \text{Gross Income} - \text{Total Expenditure (TE)}$$

6

$$\text{Gross Income (GI)} = \text{Grain Yield (GY)} \times \text{Sale Price of the product}$$

7

Gross income was calculated by multiplying grain yield (GY) by the prevailing local market price of quinoa grain at the time of harvest for the 2021-22, 2022-23, and 2023-24 seasons, respectively) (Eq. 9). The net income was obtained by subtracting total expenditure from gross income (Eq. 8). The benefit-cost ratio (BCR) is calculated for each subplot using the proposed method by as;

$$\text{Benefit - cost ratio (BCR)} = \frac{\text{Net income (NI)}}{\text{Total Expenditure (TE)}}$$

8

All prices and costs are calculated in Pakistani Rupees (PKR) that reflect market conditions prevailing during each respective cropping season and converted into US Dollar (\$).

2.8 Measurement of Growth and Yield Parameters

At physiological maturity, ten plants were randomly selected from interior rows of each subplot, excluding border rows, to record plant height (cm) and panicle length (cm). Panicle weight (g) and thousand-grain weight (g) were determined after sun-drying harvested samples until constant weight. The remaining standing crops within the net harvested area of each subplot were harvested, dried, and weighed to determine grain yield (kg ha^{-1}) and biological yield (kg ha^{-1}). Harvest index (HI), Eq. (9), was calculated as the ratio of grain yield to biological yield (BY) or total aboveground biomass (DM), expressed as a percentage (Donald & Hamblin, 1976).

$$\text{Harvest Index (HI)} = \frac{\text{Grain Yield (GY)}}{\text{Aboveground dry matter (DM) or Biological yield (BY)}}$$

9

2.9 Statistical Analysis

All recorded data were subjected to analysis of variance (ANOVA) using a split-plot model with irrigation as main plot factor and nitrogen rate as subplot factor. Year (season) was included as a fixed effect in the model to account for inter-seasonal climatic variability, and year $\times$ treatment interactions were tested for all response variables. Where year $\times$ treatment interactions were non-significant ($p > 0.05$), data were pooled across seasons, and means are presented as three-season averages. Where significant interactions were

detected, data are presented separately by season. Homogeneity of variance was verified using Levene's test prior to ANOVA (Levene, 1960; O'Neill & Mathews, 2002). Treatment means were compared using the least significant difference (LSD) test at $p \leq 0.05$. All statistical analyses were performed using Statistix version 8.1 (Analytical Software, 2000).

3. Results

3.1. Growth and Yield Component Traits

Plant height, panicle length, panicle weight, and 1000-grain weight were significantly affected by the irrigation $\times$ N interaction in all three growing seasons ($P \leq 0.01$; Table 1, Fig. 3).

Plant height increased progressively with increasing nitrogen rate and irrigation frequency, reaching a maximum under I_4N_4 in all three years (105.4, 97.4, and 91.3 cm in years 2021-22, 2022-23, and 2023-24, respectively; Fig. 3a-c), while minimum Plant height (58.0 cm) was recorded under I_1N_1 in Year 2023-24 (Fig. 3c). The year-wise ordering (Year 2021-22 > Year 2022-23 > Year 2023-24) was consistent across treatments and is attributable to the progressively cooler and shorter growing-season conditions observed in Year 2023-24 (Fig. 1).

Main panicle length was likewise maximized under I_4N_4 , with values of 33.5, 34.4, and 32.9 cm in 2021-22, 2022-23, and 2023-24, respectively (Table 1), and minimized under the unfertilized, single-irrigation treatment (I_1N_1), where values of 15.9, 15.2, and 13.9 cm were recorded across the same three seasons ($LSD_{0.05} = 0.57, 0.51, \text{ and } 0.61 \text{ cm}$ for 2021-22 through 2023-24, respectively; grand means = 25.4, 24.9, and 24.0 cm).

Panicle weight responded similarly to the irrigation $\times$ nitrogen interaction, with the highest values recorded under I_3N_4 (78.3, 83.9, and 79.0 g in 2021-22, 2022-23, and 2023-24, respectively) and the lowest (50.2, 47.9, and 42.6 g) under I_1N_1 ($LSD_{0.05} = 0.60, 0.76, \text{ and } 0.79 \text{ g}$; grand means = 64.5, 65.3, and 61.5 g across the three seasons).

The 1000-grain weight followed the same general pattern as panicle weight, with I_3N_4 producing the heaviest grains across all three seasons (2.85, 2.95, and 2.78 g in 2021-22, 2022-23, and 2023-24, respectively; $LSD_{0.05} = 0.11, 0.05, \text{ and } 0.05 \text{ g}$; grand means = 2.23, 2.23, and 2.08 g).

3.2. Grain Yield and Biological Yield

Grain yield and biological yield were significantly affected by the irrigation $\times$ nitrogen interaction in all three seasons ($P \leq 0.01$; Table 2). The I_3N_4 treatment produced highest grain yield in each season, with values of 1066.9, 1303.6, and 1017.2 kg ha⁻¹ in 2021-22, 2022-23, and 2023-24, respectively ($LSD_{0.05} = 17.74, 12.17, \text{ and } 14.68 \text{ kg ha}^{-1}$; grand means = 694.8, 716.6, and 616.0 kg ha⁻¹). Lowest grain yield was recorded under I_1N_1 (300.6, 283.9, and 197.2 kg ha⁻¹ across the three seasons, respectively).

The seasonal ranking of grain yield under I_3N_4 (2022-23 > 2021-22 > 2023-24) was mirrored by biological yield under I_4N_4 , the treatment that produced the greatest biomass in each season (3524.4, 3660.5, and

3452.9 kg ha⁻¹ in 2021-22, 2022-23, and 2023-24, respectively; LSD_{0.05} = 84.19, 74.67, and 64.66 kg ha⁻¹; grand means = 2589.2, 2514.2, and 2343.6 kg ha⁻¹). The lowest biological yield was recorded under I₁N₁ (1853.0, 1565.7, and 1438.3 kg ha⁻¹ across 2021-22 through 2023-24, respectively).

3.3. Harvest Index and Water Use Efficiency

Harvest index (HI) and WUE were significantly affected by the irrigation × N interaction in all three seasons ($P \leq 0.01$; Fig. 3). The highest HI (0.39) was recorded under I₃N₄ in 2021-22 and 2022-23, while the highest HI in 2023-24 (0.32) was recorded under I₂N₃ (Fig. 3a-c). The lowest HI in all three seasons was recorded under I₁N₁.

WUE reached its highest values under I₂N₄, with approximate values of 1.95, 1.96, and 1.78 kg m⁻³ in 2021-22, 2022-23, and 2023-24, respectively (Fig. 3a-c), placing this treatment within the top statistical grouping alongside I₃N₄ and I₄N₄ in each season. This pattern indicates that I₂N₄ achieved grain yields comparable to those of higher-irrigation treatments while requiring less applied water, resulting in superior water productivity relative to treatments receiving three or four irrigation events at the same nitrogen rate.

3.4. Benefit-Cost Ratio

BCR was significantly affected by irrigation × nitrogen interaction in all three seasons ($P \leq 0.01$; Table 2). In 2022-23 and 2023-24, the highest BCR was recorded under I₃N₄ (4.11 and 2.66, respectively). In 2021-22, the highest BCR (3.56) was recorded under I₃N₃, marginally exceeding the BCR obtained under I₃N₄ in the same season (3.42), indicating that at the lower irrigation frequency of I₃, the 80 kg N ha⁻¹ rate provided a slightly more favorable cost-to-return ratio than 120 kg N ha⁻¹ rate in 2021-22 specifically (LSD_{0.05} = 0.08, 0.05, and 0.06 for 2021-22 through 2023-24, respectively; grand means = 2.08, 1.98, and 1.42).

The lowest BCR (-0.12) was recorded under I₁N₁ in 2023-24, corresponding to a net economic loss under this treatment (Table 2; see also Section 3.6).

3.5. Nitrogen Use Efficiency Indices

PFPN, ANUE and ENUE were significantly affected by the irrigation × N interaction in all three seasons ($P \leq 0.01$; Fig. 4a-c). Among the nitrogen-fertilized treatments, I₄N₂ (40 kg N ha⁻¹ under four irrigation events) consistently produced the highest or near-highest values of PFPN, ANUE, and ENUE across all three seasons, indicating that this moderate nitrogen rate, when paired with adequate irrigation, achieved the most efficient conversion of applied nitrogen into yield and economic return.

In contrast, the higher N rates (80 and 120 kg N ha⁻¹) showed progressively lower values for all three indices relative to I₄N₂, despite producing higher absolute grain yields (Table 2), reflecting diminishing marginal returns to nitrogen application beyond 40 kg ha⁻¹.

ENUE was highest in 2021-22 and lowest in 2023-24 across nearly all treatments (Fig. 4a-c). This decline coincided with a substantial depreciation of the Pakistani rupee against the US dollar over the study period (185, 283, and 277 PKR per US\$ in 2021-22, 2022-23, and 2023-24, respectively; Fig. 4), which increased the

US\$-denominated cost of nitrogen fertilizer (N-value) and thereby reduced ENUE in later seasons, independent of any change in the physical nitrogen application rates (which were held constant by design across all three seasons).

3.6. Economic Analysis: Total Expenditure, Gross Income, and Net Income

Total expenditure (TE), gross income (GI), and net income (NI), expressed in US\$ ha⁻¹, were significantly affected by irrigation regime and nitrogen rate in all three seasons (Fig. 4d-f). TE increased with increasing nitrogen rate, reflecting the cost of additional urea applications, and to a lesser extent with increasing irrigation frequency, reflecting water delivery costs.

GI and NI were consistently highest under I₃N₄ across all three seasons (Fig. 4d-f). However, the seasonal ranking of GI and NI in US\$ terms (2021-22 > 2022-23 > 2023-24) differed from the ranking of grain yield in physical units for the same treatment (2022-23 > 2021-22 > 2023-24; Table 2). This divergence is attributable to the exchange-rate depreciation noted above (Section 3.5): the same physical yield converted to a smaller US\$ value in 2022-23 and 2023-24 than in 2021-22, owing to the higher PKR-per-US\$ rate in those seasons.

The lowest NI (-39.0 US\$ ha⁻¹) was recorded under I₁N₁ in 2023-24 (Fig. 4f), corresponding to the negative BCR (-0.12) reported for the same treatment and season in Section 3.4; both values describe the same underlying economic outcome (a net loss under the unfertilized, single-irrigation treatment in 2023-24), expressed as an absolute return (NI) and as a return ratio (BCR), respectively.

4. Discussion

4.1. Growth Responses to Irrigation and Nitrogen

Plant height, panicle length, panicle weight, and 1000-grain weight all increased with irrigation frequency and nitrogen rate, reflecting better nutrient uptake, photosynthesis, and assimilate translocation under improved soil moisture (Mirsafi et al., 2024;). Water and nitrogen availability were therefore the main limiting factors for growth at this site. Quinoa exhibits a remarkable capacity to maintain homeostasis between water loss and water uptake, effectively mitigating water deficits through multiple adaptive mechanisms (Jaikishun et al., 2019).

Plant height followed a consistent seasonal pattern (2021-22 > 2022-23 > 2023-24), coinciding with cooler, more variable temperatures during Dec-Feb, 2023-24 (Fig. 1) and minimal rainfall across all seasons (Fig. 2). Quinoa is known to be sensitive to temperature during early vegetative growth (Bertero et al., 1999b; Bois et al., 2006; Hinojosa et al., 2019; Yang et al., 2016), and this likely explains the seasonal differences observed.

Panicle weight under I₃N₄ did not exceed that under I₄N₄ (Table 1), suggesting that beyond this point, extra irrigation favored continued vegetative growth over reproductive sink development (Awa et al., 2024; Kaya et al., 2015; Passioura, 2006). This pattern suggests a source-sink imbalance, where excessive water availability shifts assimilate allocation toward foliage and stem biomass at the expense of grain-filling capacity (Farooq et al., 2014; Paul et al., 2020). This aligns with findings that drought stress affects secondary panicles seed

yield and sink strength, highlighting the dichotomy between seed quantity and quality under water-limiting versus excessive water conditions (Maestro-Gaitán et al., 2023).

4.2. The Yield Potential Gap

Grain yield under the best treatment (I_3N_4) reached only 1000–1300 kg ha⁻¹ against a reported yield potential of 3200 kg ha⁻¹ for UAF-Q7 and a reported 1500–2000 kg ha⁻¹ averaged yield potential as a baseline for selection of quinoa genotypes (Afzal et al., 2022). The low soil organic matter (0.51%) and available P (7.81 mg kg⁻¹) likely limited assimilate translocation to grain even at the highest N rate, independent of irrigation/N treatments (Bouras et al., 2022; Buckland et al., 2018; Hirich et al., 2014; Jorfi et al., 2022). Similarly, Shams (2012) also evaluated quinoa's response to elevated N rates in sandy soils (last week of October), reporting that maximum economic yield of 1100 kg ha⁻¹ was achieved with an application of 360 kg N ha⁻¹, representing an 11-fold increase over the untreated control. Furthermore, the optimum and favorable sowing time for successful quinoa production is from mid-October to mid-December and the mid- and last week of November. (Basma et al., 2014; Rizvi et al., 2017; Hafeez et al., 2022; Afzal et al., 2022; Hanif & Afzal, 2026b). Therefore, sowing date adjustment is also play pivotal role rather than N fertilization rate and drought stress in successful and sustainable quinoa crop production.

4.3. Grain Yield vs. Biological Yield

Biological yield increased significantly with irrigation, peaking under I_4N_4 (Table 2), but grain yield and harvest index at N_4 peaked one irrigation level earlier, at I_3N_4 . The extra water under I_4 thus went mainly into vegetative biomass rather than grain, consistent with reports that excess moisture shifts partitioning away from reproductive structures in quinoa (Bahrami et al., 2022a). The physiological mechanism underlying this partitioning shift involves regulation of stomatal conductance and dynamics of photosynthate translocation. Under optimal water conditions, quinoa maintains high stomatal conductance and transpiration rates, supporting vigorous canopy development (Rathore & Kumar, 2021). However, excessive moisture can induce imbalances in carbohydrate-nitrogen metabolism, reducing the availability of photosynthates for grain filling (Irfan et al., 2010).

4.4. Water Use Efficiency vs. Yield

Drought stress reduced total grain yield and water use efficiency (Geerts et al., 2008), whereas under severe water limitation, drought-tolerant quinoa genotypes outperformed sensitive genotypes by maintaining higher seed yield per plant and superior yield components, including more branches per plant, greater leaf area, and a higher chlorophyll index (Al-Naggar et al., 2017a). Treatment I_3N_4 maximized yield, but I_2N_4 maximized WUE. The third irrigation under N_4 added little yield relative to its water cost. This aligns with evidence that efficient water/nutrient management can increase quinoa water productivity without maximal irrigation (Kumar et al., 2024; Sezen et al., 2025; Sun et al., 2025). In water-scarce regions, such as Multan, the I_2N_4 treatment represents a more pragmatic management strategy, as water availability, not the theoretical yield potential, constitutes the primary constraint limiting quinoa crop performance (Gavino et al., 2026).

4.5. Nitrogen Use Efficiency

Treatment I_4N_2 (40 kg N ha^{-1} , four irrigations) gave the highest PFPN, ANUE, and ENUE of all treatments, despite lower absolute yield than $80\text{--}120 \text{ kg N ha}^{-1}$ rates. Under adequate irrigation, applied N is taken up more efficiently; excess N is more prone to loss, lowering NUE (Abou-amer & Kamel, 2011; Deng et al., 2026). Li et al. (2025) reported that excessive N fertilization inhibits dry matter accumulation and reduces NUE in quinoa. Similarly, Bahrami et al. (2022) identified an optimum nitrogen application rate of 250 kg ha^{-1} and 0.75 full irrigation (FI) as the conditions yielding the highest seed WUE, implying that both insufficient and excessive water or nitrogen reduce efficiency. As with WUE, the yield-optimal (I_3N_4) and efficiency-optimal (I_4N_2) treatments diverge from a familiar trade-off in N management (Deng et al., 2024; Hinojosa et al., 2018; Johora et al., 2026; Sinclair & Rufty, 2012). The I_3N_4 treatment is more appropriate for yield-focused production systems, whereas I_4N_2 is better suited to contexts where fertilizer cost, N surpluses, or environmental N losses are primary concerns, achieving comparable performance at approximately one-third of the N input.

The NUE in quinoa declined when N application exceeded 40 kg ha^{-1} in an experiment conducted in Morocco, indicating diminishing returns and potential nutrient imbalances at higher N rates (Taaime, El Mejahed, et al., 2023). This finding aligns with the observed pattern in our study, in which the highest N rate (N_4) likely exceeded the optimal threshold for quinoa, without compensatory improvements in soil organic matter or phosphorus availability. These findings are also consistent with findings under sandy soil conditions in Egypt, where increasing N rate from 0 to 160 kg ha^{-1} significantly increased grain yield but reduced NUE from 5.52 to 4.31 (Almadini, E. Badran, et al., 2019).

4.6. Economic Performance/Analysis

Treatment I_3N_4 yielded the highest gross income and net returns among all treatments in each of the three growing seasons (2021-22, 2022-23, and 2023-24; $p \leq 0.05$). Furthermore, I_3N_4 attained the highest benefit-cost ratio (BCR) in 2022-23 and 2023-24, with values of 4.11 and 2.66, respectively. Irrigation treatment I_4 never outperformed I_3 on BCR at the same N rate; the fourth irrigation's cost wasn't recovered, consistent with its biomass-not-grain effect (Section 4.3). In 2021-22 only, I_3N_3 treatment (BCR 3.56) slightly exceeded I_3N_4 (3.42), suggesting a marginally negative return to the last 40 kg N that year, a minor exception that doesn't change the treatment I_3N_4 's overall standing as the most consistently profitable treatment in terms of grain yield. This underscores the critical need to optimize both management practices and genotype selection to maximize farm profitability (Chaudhary et al., 2024; Hanif & Afzal, 2026a). Economic analysis from Morocco indicates that quinoa seed production costs range from $3.71\text{--}4.70 \text{ USD kg}^{-1}$ under rainfed, manual production (Rehamna region) but decrease to 2.07 USD kg^{-1} under mechanized production with adequate rainfall ($> 350 \text{ mm}$; Berrechid region), confirming that mechanization and improved water management reduce unit costs by 54–56% (Benatti, 2017).

4.7. Currency Effects on Multi-Season Comparisons

Substantial Pakistani rupee depreciation against the US dollar during the study period ($185 \rightarrow 283 \rightarrow 277 \text{ PKR/US\$}$) introduces a methodological complication distinct from biological and economic patterns. Grain yield (physical quantity) and grain value (monetary quantity) are linked only through exchange rates and

market prices; thus, economic indicators reported in a single foreign currency across multiple seasons in a currency-volatile economy reflect macroeconomic conditions concurrent with agronomic performance (Kristinek & Anderson, 2002). The lowest net income ($NI = -39.0 \text{ US\$ ha}^{-1}$) and benefit-cost ratio ($BCR = -0.12$) under treatment I_1N_1 in 2023-24 confirm that omitting nitrogen combined with minimal irrigation resulted in a net economic loss during the most constrained season. This finding reinforces that neither nitrogen fertilizer nor adequate irrigation should be omitted under Multan's semi-arid conditions, as both inputs are essential for achieving positive economic returns in quinoa production (Iqbal et al., 2019).

5. Limitations and Future Work

This study was conducted at a single site over three seasons using one cultivar (UAF-Q7, currently the only officially released quinoa variety in Pakistan), and soil nitrogen and phosphorus status were characterized only prior to sowing rather than monitored throughout crop growth; consequently, the pronounced gap between observed yields ($1000\text{--}1300 \text{ kg ha}^{-1}$) and the cultivar's reported potential (3200 kg ha^{-1}) could not be definitively attributed to phosphorus limitation versus water constraints versus interannual climatic variability (Figs. 1 and 2). Future research should prioritize multi-location trials with multiple sowing dates, in-season soil nitrogen, nitrogen dynamics (NO_3^- , NH_4^+) and phosphorus monitoring to test the phosphorus-limitation hypothesis and evaluate phosphorus and soil fertility amendments alongside irrigation-nitrogen management along with the validation of crop simulation model (e.g., DSSAT-CSM), coupled with life-cycle assessment to quantify the water footprint, nitrogen losses measurement and mitigation, GHG emissions, and environmental sustainability of quinoa production in Pakistan.

6. Conclusion

This three-year field study demonstrates that grain yield, water use efficiency, and nitrogen use efficiency of UAF-Q7 quinoa respond to irrigation frequency and nitrogen rate in distinct and partially divergent ways under the semi-arid conditions, and no single treatment combination optimized all three simultaneously. Three irrigation events combined with 120 kg N ha^{-1} (I_3N_4) produced the highest grain yield ($1017\text{--}1304 \text{ kg ha}^{-1}$ across seasons) and highest benefit-cost ratio (up to 4.11). The highest water-use efficiency (up to 1.96 kg m^{-3}) was achieved with two irrigation events at 120 kg N ha^{-1} (I_2N_4). Therefore, selection among I_3N_4 , I_2N_4 , and I_4N_2 should be prioritized according to their objective, such as yield and profit, water productivity, or nitrogen-use efficiency. Notably, even the best-performing treatment (I_3N_4) yielded only 32–41% of the 3200 kg ha^{-1} potential reported for UAF-Q7, indicating that factors beyond irrigation and nitrogen management most plausibly the low native soil organic matter (0.51%) and available phosphorus (7.81 mg kg^{-1}) at this site, together with the seasonal temperature and rainfall variability documented across the three growing seasons constrained attainable yield. Closing this gap will require future trials that combine the irrigation–nitrogen framework established here with targeted multiple-sowing and soil-fertility amendments, alongside in-season nutrient monitoring, to determine whether the yield ceiling for UAF-Q7 can be raised under field conditions representative of semi-arid conditions.

Declarations

Data availability

All data generated for this manuscript are included within the text, figures, and tables.

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Contributions

A.A.W.: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **D.A.:** Conceptualization, Data curation, Methodology, Formal analysis, Writing – review & editing. **F.W.K.:** Investigation, Writing – review & editing. **D.A.B.G.:** Investigation, Writing – review & editing. **A.B.:** Investigation, Writing – review & editing. **Abdul Rehman:** Conceptualization, Methodology, Writing – review & editing. **S.A.:** Supervision, Methodology, Resources, Project administration, Funding acquisition, Validation, Writing – review & editing. All authors reviewed, revised, and approved the final version of the manuscript.

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Ethics declarations

Ethics approval

Not applicable.

Consent to participate

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Consent for publication

Consent for publication was obtained from all identifiable individuals.

Conflict of interest

The authors declare no competing interests.

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Tables

Table 1. Combined effects of irrigation regime and nitrogen application rate on main panicle length, main panicle weight, and 1000-grain weight of quinoa (cv. UAF-Q7) across three growing seasons (2021-22, 2022-23, and 2023-24).

Treats.		Main panicle length (cm)			Main panicle weight (g)			1000 grain weight (g)		
		Year 2021-22	Year 2022-23	Year 2023-24	Year 2021-22	Year 2022-23	Year 2023-24	Year 2021-22	Year 2022-23	Year 2023-24
I_1	0 kg N ha ⁻¹	15.9 l	15.2 o	13.9 n	50.2 n	47.9 m	42.6 o	1.58 h	1.53 k	1.42 l
I_2		23.0 h	20.4 k	20.0 j	54.3 l	53.6 jk	45.2 n	1.84 fg	1.82 i	1.52 k
I_3		24.0 g	23.0 j	21.6 i	57.2 i	57.8 i	54.9 j	1.91 f	1.89 h	1.73 j
I_4		24.2 g	23.6 i	22.6 h	59.2 h	59.2 h	58.7 i	1.90 f	1.94 h	1.86 i
I_1	40 kg N ha ⁻¹	16.4 k	15.7 n	15.1 m	52.6 m	50.6 l	46.1m	1.93 f	1.63 j	1.49 k
I_2		26.4 e	25.6 h	24.4 g	60.4 g	58.8 h	59.5 h	2.04 e	2.16 f	2.05 h
I_3		28.2 d	27.7 f	26.9 e	63.4 f	66.7 g	61.7 g	2.14 de	2.20 f	2.11 g
I_4		29.8 c	28.6 e	27.5 d	71.1 e	73.5 f	67.4 f	2.25 d	2.28 e	2.17 f
I_1	80 kg N ha ⁻¹	18.8 j	17.9 m	16.8 l	55.3 k	53.3 k	50.3 l	1.77 g	1.77 i	1.71 j
I_2		28.1 d	28.2 ef	27.7 d	72.2 d	74.2 e	72.2 d	2.40 c	2.33 e	2.30 e
I_3		29.7 c	30.4 d	29.3 c	75.9 b	79.5 b	75.2 b	2.76 ab	2.91 a	2.66 b
I_4		31.6 b	32.3 b	31.2 b	75.3 b	77.3 cd	73.3 c	2.67 b	2.77 c	2.57 c
I_1	120 kg N ha ⁻¹	19.9 i	18.9 l	17.8 k	56.3 j	54.3 j	53.6 k	2.21 d	2.02 g	1.88 i
I_2		25.7 f	26.3 g	25.1 f	74.5 c	76.5 d	71.2 e	2.47 c	2.55 d	2.38 d
I_3		31.3 b	31.5 c	31.1 b	78.3 a	83.9 a	79.0 a	2.85 a	2.95 a	2.78 a
I_4		33.5 a	34.4 a	32.9 a	75.5 b	77.8 c	73.3 c	2.83 a	2.84 b	2.63 b
Significance		**	**	**	**	**	**	**	**	**
LSD 5%		0.57	0.51	0.61	0.60	0.76	0.79	0.11	0.05	0.05
Grand Mean		25.4	24.9	24	64.5	65.3	61.5	2.23	2.23	2.08

Note: I_1 – I_4 = irrigation regimes (one to four irrigation events at 35, 75, 105, and 125 days after sowing, respectively); N_1 – N_4 = nitrogen application rates (0, 40, 80, and 120 kg N ha⁻¹, respectively). Means within each

column followed by different letters differ significantly at $P \leq 0.05$ according to the least significant difference (LSD) test. ** indicates significance at $P \leq 0.01$.

Table 2: Combined effects of irrigation regime and nitrogen application rate on grain yield, biological yield, and benefit-cost ratio of quinoa (cv. UAF-Q7) across three growing seasons (2021-22, 2022-23, and 2023–24).

Treats.		Grain yield (kg/ha)			Biological yield (kg/ha)			Benefits-Cost ratio		
		Year 2021-22	Year 2022-23	Year 2023-24	Year 2021-22	Year 2022-23	Year 2023-24	Year 2021-22	Year 2022-23	Year 2023-24
I_1	0 kg N ha ⁻¹	300.6 m	283.9 o	197.2 o	1853 m	1565.7 n	1438.3 n	0.46 k	0.29 n	-0.12 l
I_2		374.0 k	337.3m	259.3 n	2044 k	1851.3 l	1591.1 m	0.82 h	0.53 l	0.16 j
I_3		452.1 i	462.1 k	425.8 k	2251.2 i	2162.6 j	2108.7 i	1.20 g	1.10 j	0.91 h
I_4		466.3 i	483.0 j	483.0 j	2648.3 g	2428.1 i	2267 h	1.27 g	1.20 i	1.16 g
I_1	40 kg N ha ⁻¹	349.9 l	319.9 n	251.0 n	1953.6 l	1680.5m	1529.5 m	0.61 j	0.38 m	0.04 k
I_2		681.7 h	665.0 i	580.3 i	2148.7 j	1953.2 k	1789.5 k	2.14 f	1.87 h	1.41 f
I_3		724.4 g	747.8 h	705.3 h	2409.1 h	2652.0 g	2365.8 g	2.33 e	2.23 g	1.93 e
I_4		896.6 f	916.6 g	816.6 g	2944.6 e	3086.7 e	2882.8 e	3.13 cd	2.96 e	2.39 b
I_1	80 kg N ha ⁻¹	390.6 k	340.6m	301.9 m	2048.9 k	1810.7 l	1683.4 l	0.70 i	0.40 m	0.16 j
I_2		952.5 e	935.8 f	835.8 f	2733.3 f	2536.1 h	2340.8 g	3.15 c	2.85 f	2.22 d
I_3		1044.7 b	1228.0b	939.6 b	3091.8 d	3193.9 d	3074.1 d	3.56 a	4.05 b	2.62 a
I_4		999.6 c	1012.9d	877.3 e	3422.5 b	3544.6 b	3266.3 b	3.36 b	3.16 c	2.38 b
I_1	120 kg N ha ⁻¹	430.1 j	413.4 l	361.3 l	2178.1 ij	1947.3 k	1885.6 j	0.78 hi	0.62 k	0.30 i
I_2		979.5 d	986.2 e	892.8 d	2954.4 e	2813.6 f	2659.5 f	3.06 d	2.87 f	2.22 d
I_3		1066.9 a	1303.6a	1017.2 a	3221.8 c	3339.9 c	3162.9 c	3.42 b	4.11 a	2.66 a
I_4		1006.9 c	1030.2c	910.9 c	3524.4 a	3660.5 a	3452.9 a	3.17 c	3.04 d	2.28 c
Significance		**	**	**	**	**	**	**	**	**
LSD 5%		17.74	12.17	14.68	84.19	74.67	64.66	0.08	0.05	0.06
Grand Mean		694.77	716.64	615.95	2589.2	2514.2	2343.6	2.08	1.98	1.42

Note: I₁-I₄ = irrigation regimes (one to four irrigation events at 35, 75, 105, and 125 days after sowing, respectively); N₁-N₄ = nitrogen application rates (0, 40, 80, and 120 kg N ha⁻¹, respectively). Means within each column followed by different letters differ significantly at P ≤ 0.05 according to the least significant difference (LSD) test. ** indicates significance at P ≤ 0.01.

Figures

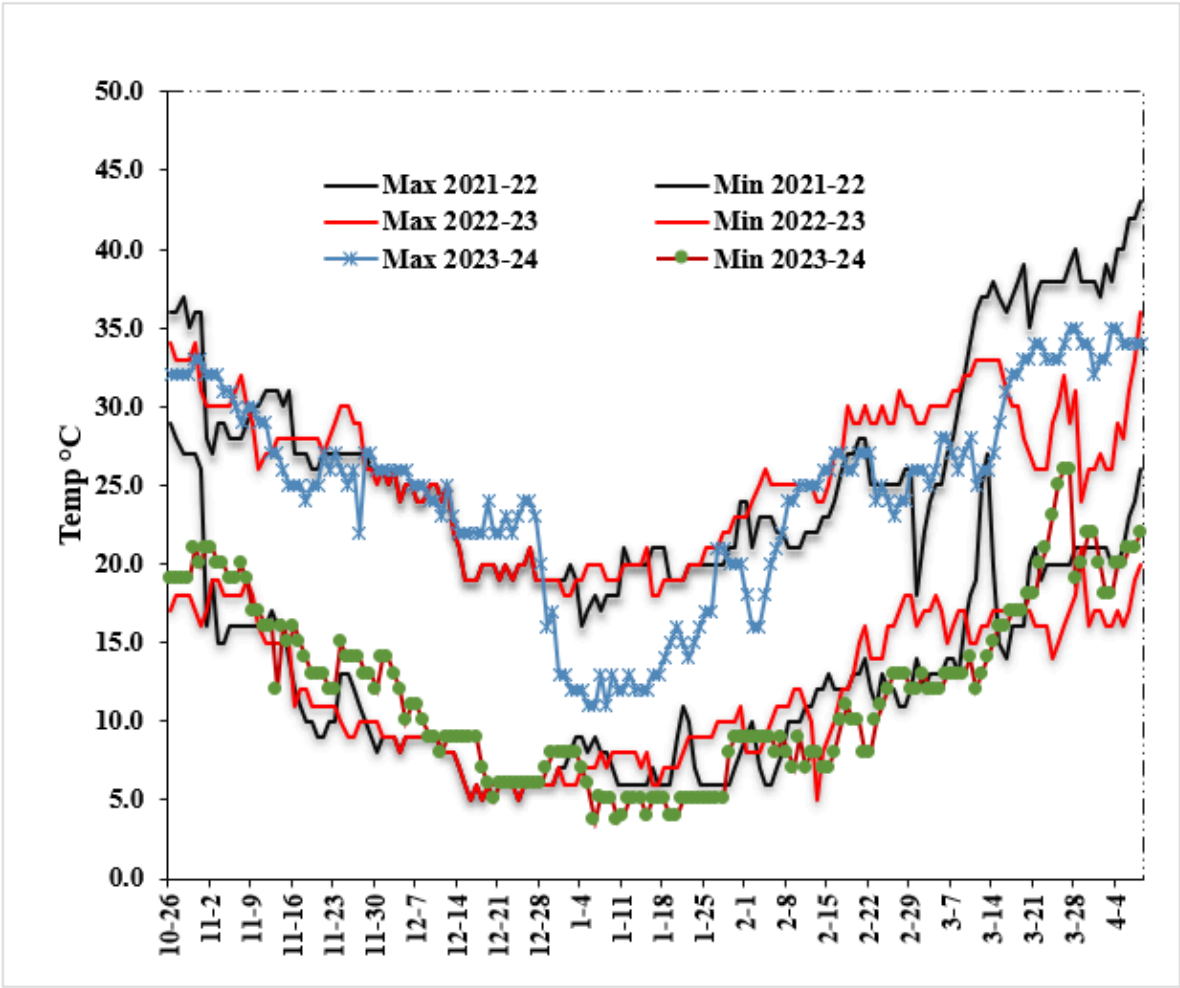


Figure 1

Daily maximum and minimum mean air temperature (°C) recorded at the experimental site during the 2021-22, 2022-23, and 2023-24 winter cropping seasons.

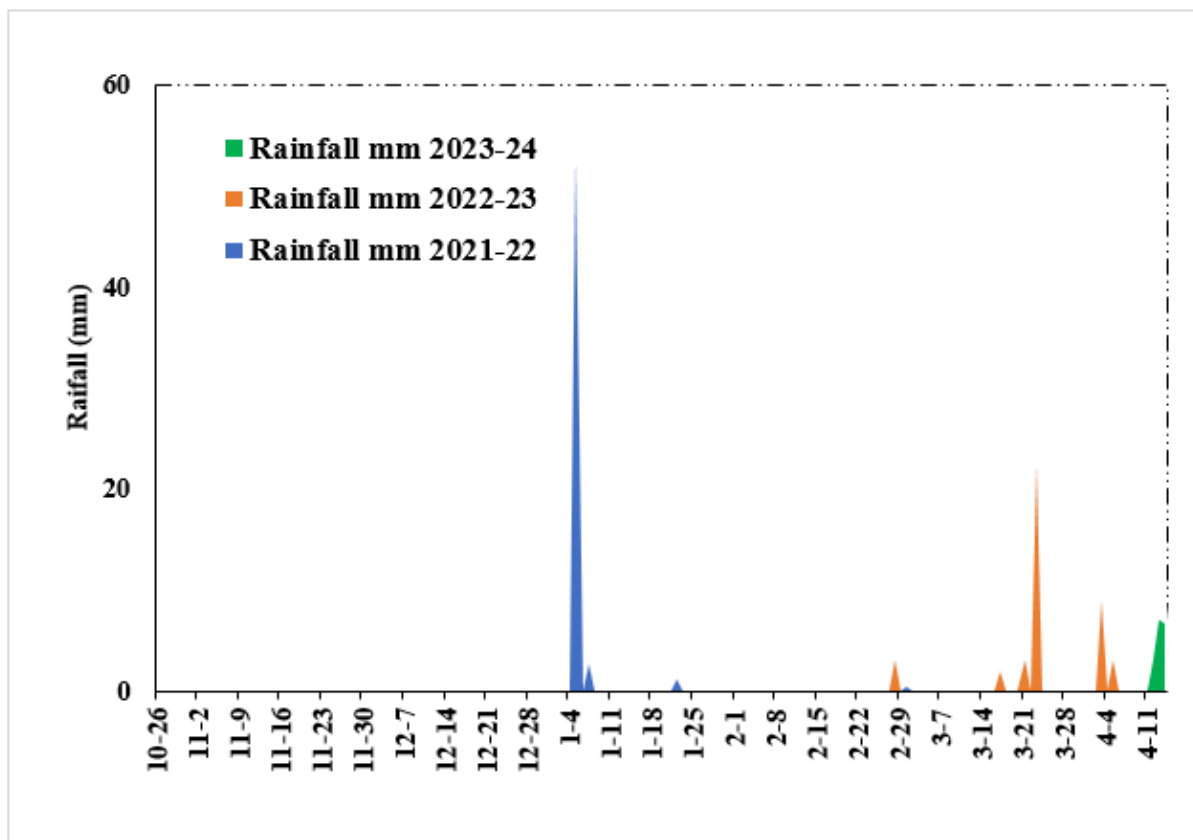


Figure 2

Cumulative rainfall (mm) recorded at the experimental site during the 2021-22, 2022-23, and 2023-24 winter cropping seasons.

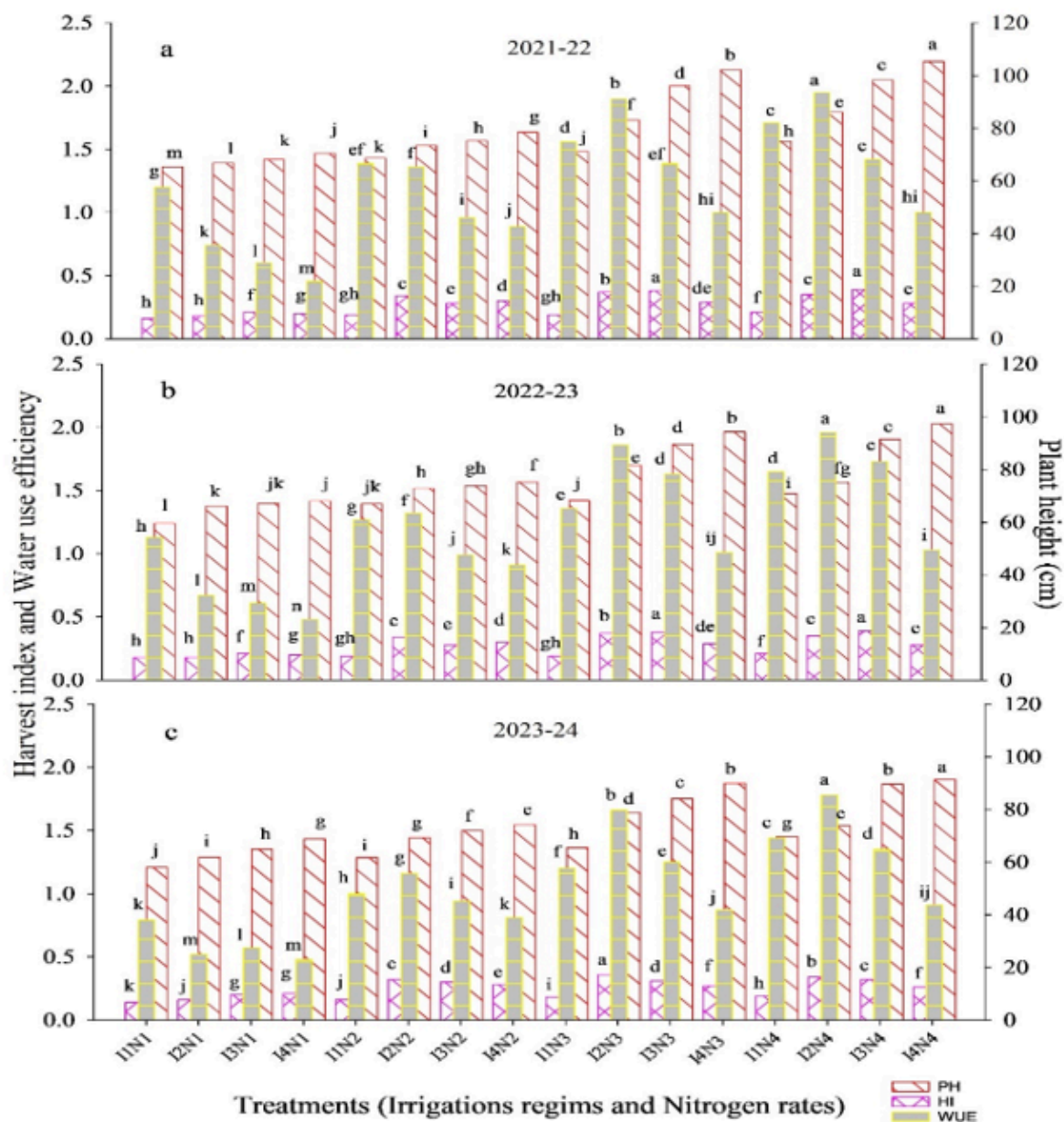


Figure 3

Combined effects of irrigation regime and nitrogen application rate on plant height (PH, cm), harvest index (HI), and water use efficiency (WUE, kg m⁻³) of quinoa (cv. UAF-Q7) during (a) 2021-22, (b) 2022-23, and (c) 2023-24. I₁-I₄ = irrigation regimes (one to four irrigation events at 35, 75, 105, and 125 days after sowing, respectively); N₁-N₄ = nitrogen application rates (0, 40, 80, and 120 kg N ha⁻¹, respectively). Bars and columns labeled with different letters differ significantly at $P \leq 0.05$ according to the least significant difference (LSD) test.

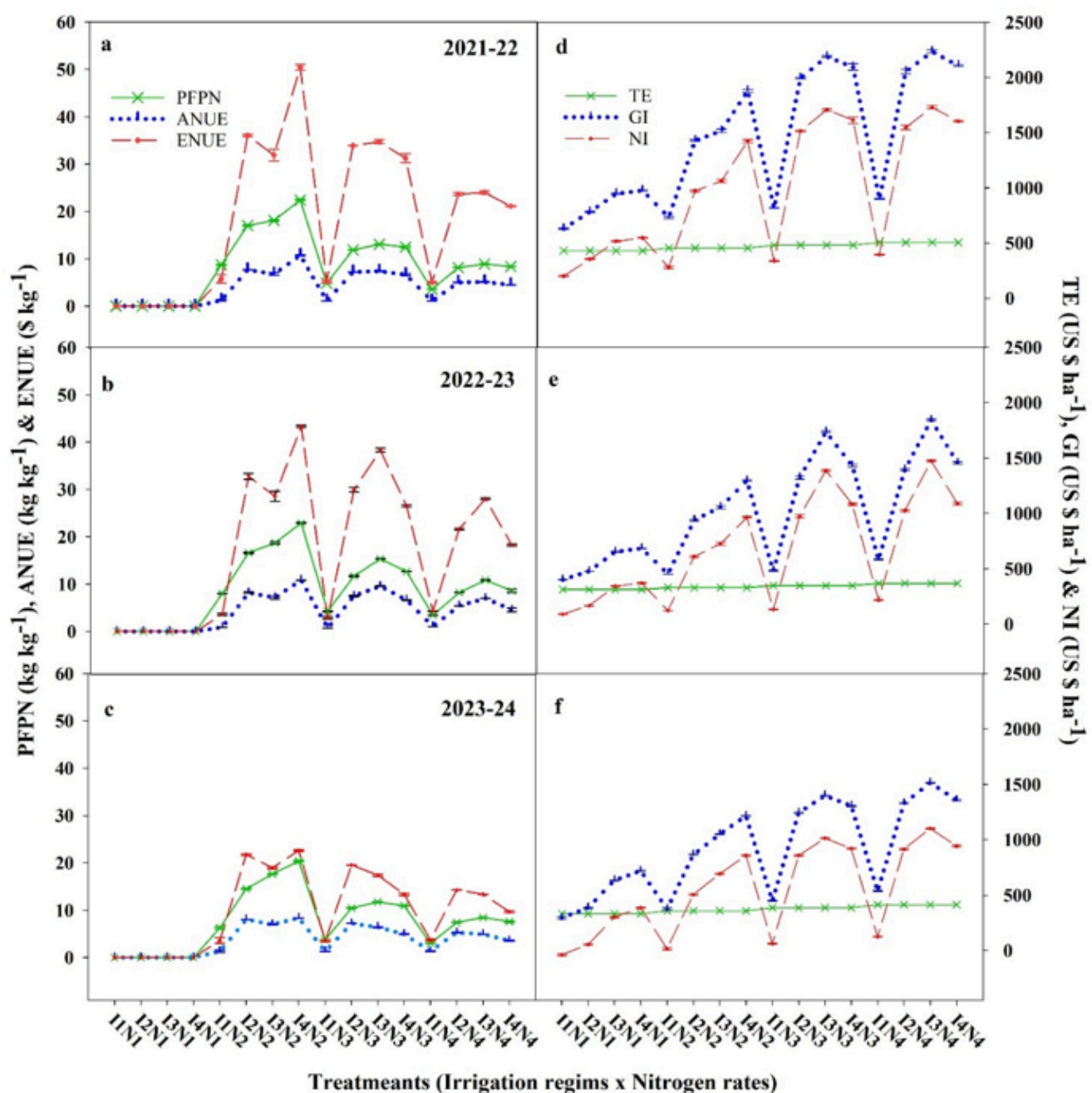


Figure 4

Combined effects of irrigation regime and nitrogen application rate on (a-c) partial factor productivity of nitrogen (PFPN, kg kg⁻¹), agronomic nitrogen use efficiency (ANUE, kg kg⁻¹), and economic nitrogen use efficiency (ENUE, US \$ kg⁻¹), and (d-f) total expenditure (TE), gross income (GI), and net income (NI), all expressed in US\$ ha⁻¹, of quinoa (cv. UAF-Q7) during (a, d) 2021-22, (b, e) 2022-23, and (c, f) 2023-24. I₁-I₄ = irrigation regimes (one to four irrigation events at 35, 75, 105, and 125 days after sowing, respectively); N₁-N₄ = nitrogen application rates (0, 40, 80, and 120 kg N ha⁻¹, respectively). Currency conversion rates applied: 1 US\$ = 185 PKR (2021-22), 283 PKR (2022-23), and 277 PKR (2023-24).