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Unraveling the Influence of Water and Nitrogen Management on Quinoa (*Chenopodium quinoa* Willd.) Agronomic and Yield Traits

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Abstract: Effective management is crucial to achieve the high yield potential of quinoa (*Chenopodium quinoa* Willd.), renowned for its resilience in harsh environments, to meet the rising global demand. The present study examines how varying levels of water and nitrogen affect the agronomic and yield traits of quinoa (cv. Q-36) during the two growing seasons of 2020/2021 and 2021/2022. The experiment was a 3 × 4 factorial laid out in a randomized complete block design with three replications per treatment during the two seasons of the study, as water regimes were considered the main factor, including 100%, 80%, and 60% ETc, whereas nitrogen levels were considered the sub-plot factor, comprising four levels (75, 150, 225, and 300 kgN ha^{-1}). The analysis of variance indicated that nitrogen level, irrigation regime, and irrigation regime × nitrogen level had highly significant effects ($p < 0.001$) on all studied traits, including plant height, panicle length, dry weight, seed weight, seed yield, and total yield in the two growing seasons under study. For all traits of study, the combined application of 100% ETc with 300 kgN, followed by 80% ETc with 225 kgN, resulted in the highest value of plant height, panicle length, dry weight, seed weight, seed yield, and total yield, whereas the combination of 60% ETc and 75 kgN applications resulted in the lowest value for all of the aforementioned traits. Furthermore, the water regime impacted water productivity at all nitrogen levels as the highest productivity level was recorded under the 80% ETc (0.58 kg/m^3), followed by the 100% ETc (0.54 kg/m^3), and the 60% ETc (0.52 kg/m^3). The highest water productivity rate was observed at 300 kg/ha of the nitrogen levels for 60% and 80% ETc regimes, where water productivity levels were 0.73 and 0.71 (kg/m^3), respectively. The results also indicate that the water productivity of quinoa plants is noticeably affected by both water regime and nitrogen level; as the water regimes decrease from 100% to 60% ETc, water productivity increases for all nitrogen levels. The information obtained from these results can be applied to optimize the methods for cultivating quinoa under conditions of water scarcity and minimal nitrogen availability, thus gaining an insight into the impact of these conditions on quinoa growth and yield.

Keywords: crop evapotranspiration; drip irrigation; direct effect; pairwise relationships; seed yield; quinoa (*Chenopodium quinoa* Willd.)

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1. Introduction

Environmental changes have reached critical levels in recent decades, posing an environmental threat to the food supply due to their negative impact on crop yield and quality [1]. Because most crops around the world are adapted to specific climatic conditions, many of these crops will become less productive as a result of significant climate change. It is, therefore, essential to investigate plant species as alternate crops or create new crops that can grow during these varying weather patterns. In this regard, it is crucial to take into account plant species that can grow at various altitudes or have endured for a very long time in mountainous areas [2].

Quinoa (*Chenopodium quinoa* Willd.), a traditional crop from the Andean region of South America [3], belongs to the Amaranthaceae family. The grain of quinoa has attractive nutritional properties, and this attribute has greatly increased its consumption in recent years [4]. Quinoa contains unsaturated fatty acids, antioxidants, and essential amino acids, and it is rich in Fe, Mg, fiber, and vitamins, while containing high levels of gluten-free protein [5,6]. Quinoa has extreme tolerance to various types of abiotic stresses [7–13]. Quinoa has the ability to thrive in dry climates with an annual rainfall of at least 200 mm. Research has shown that quinoa can withstand periods of drought by sustaining its water absorption process and increasing the quantities of proline and total soluble sugar. These mechanisms are crucial in maintaining the cellular turgor pressure necessary for cell expansion, particularly in stressful conditions [14]. In order to evaluate quinoa plants under water stress conditions, it is necessary to analyze and compare their morphological characteristics, such as plant height, panicle length, seed weight, and dry weight, in addition to yield and yield-related traits. The correlation between yield and morphological traits under water-limited conditions can be used to further support the need for this requirement.

Studies have shown that nitrogen, as a macronutrient, has a positive effect on quinoa seed yield. It has been suggested by some studies that the maximum quinoa yield could be achieved at 80 kg N ha^{-1}; however, yields may vary depending on the type of soil, with sandy–clay–loam soils producing higher yields [15,16]. Among those studies, Kaul et al. [15] reported that quinoa exhibited a good N response, achieving a grain yield of 3.5 t ha^{-1} at 120 kg N ha^{-1}, representing an increase in grain yield by 94% compared to the control crop. The results of other studies pinpointed that an average of 12% of yield increase was recorded when nitrogen was applied at a level of 80 to 120 kg N ha^{-1} [17]. They also concluded that the response of quinoa plants to such an N application resulted in an increase in the crop growth, yield, and quality of grains. However, other studies suggest that additional nitrogen does not necessarily influence growth or yield factors [18].

However, the effects of drought and nitrogen application on quinoa have been studied in separate studies; less studies have reported the impact of nitrogen application under different water regimes. It is worth noting that two of the most significant agricultural constraints, particularly in semi-arid areas, are water and nitrogen [19]. The devastating effects of water stress on plants receiving nitrogen applications include reducing the bioavailability of nitrogen and decreasing the levels of both diffusion and mass flow from soil solution to the rhizosphere, leading to decreased nitrogen uptake in the plants [20,21]. Nitrogen application has improved yields and water-use efficiency through enhancing the sensitivity of stomatal conductance in water-limited areas [22–26]. Based on the available information, it is expected that the utilization of N fertilizer could potentially influence the plant's mechanisms for regulating water, thereby aiding in the mitigation of dehydration and preservation of quinoa yields in situations of limited water availability [19].

It is hypothesized that varying levels of water and nitrogen fertilizer will have a significant effect on the agronomic and yield traits of quinoa. Specifically, it is expected that severe water stress will negatively impact the studied traits, particularly the yield of quinoa. However, it is expected that applications with nitrogen can mitigate the negative effects of water stress on quinoa's growth and yield. The present investigation derives its significance from conducting such water- and nitrogen-level treatments and examining their effects on the yield of quinoa, a crop known for its ability to thrive in harsh environmental conditions. The results of this study can be applied to optimize the cultivation methods for quinoa, especially under conditions of water scarcity and minimal nitrogen availability. This is particularly important in the context of global climate change, where water scarcity is expected to become more prevalent in many regions.

Therefore, the present study is conducted to evaluate the agronomic traits of quinoa under discrepant water regimes and nitrogen levels, in addition to dissecting the interrelationships among such traits using correlation and path coefficient analyses.

2. Materials and Methods

2.1. Experimental Site Description

The field trials were conducted during two growing seasons, 2020/2021 and 2021/2022, at the Research Farm of Arab El-Awammer (27°03′ N, 31°01′ E) Research Station, Agriculture Research Institute (ARC), Assuit, Egypt. Figure 1 presents a map that displays the location of the experimental site where the study was performed. The present study utilized Q-36, a quinoa cultivar developed by researchers at the National Agrarian University of La Molina in Peru, known for its favorable attribute of producing large and uniform grains. The seeds of the quinoa genotype used in this study were acquired from the Plant Breeding Unit, Plant Genetic Resources Department, Desert Research Center, Egypt. During both growing seasons of the study, 2020/2021 and 2021/2022, the seeds were planted on 3 and 8 November, respectively. The meteorological data for the experimental site during the two growing seasons are presented in Table 1. The climate in Arab El-Awammer is generally dry and hot, with low humidity throughout the year. During the summer months of June through to August, temperatures can average around 35–40 °C or even higher. During the winter months of December through to February, temperatures are milder, averaging around 15–20 °C. In terms of precipitation, the Arab El-Awammer region receives very little rainfall throughout the year, with most precipitation occurring in the winter months. The experiments were conducted in a sandy calcareous soil. Representative soil samples from the field experimental surface layer (0–25 cm) were collected before cultivation and air-dried, crushed, and sifted to pass through a 2 mm mesh. The physical and chemical properties were determined by the standard methods reported by [27,28], and the obtained results are presented in Table 2.

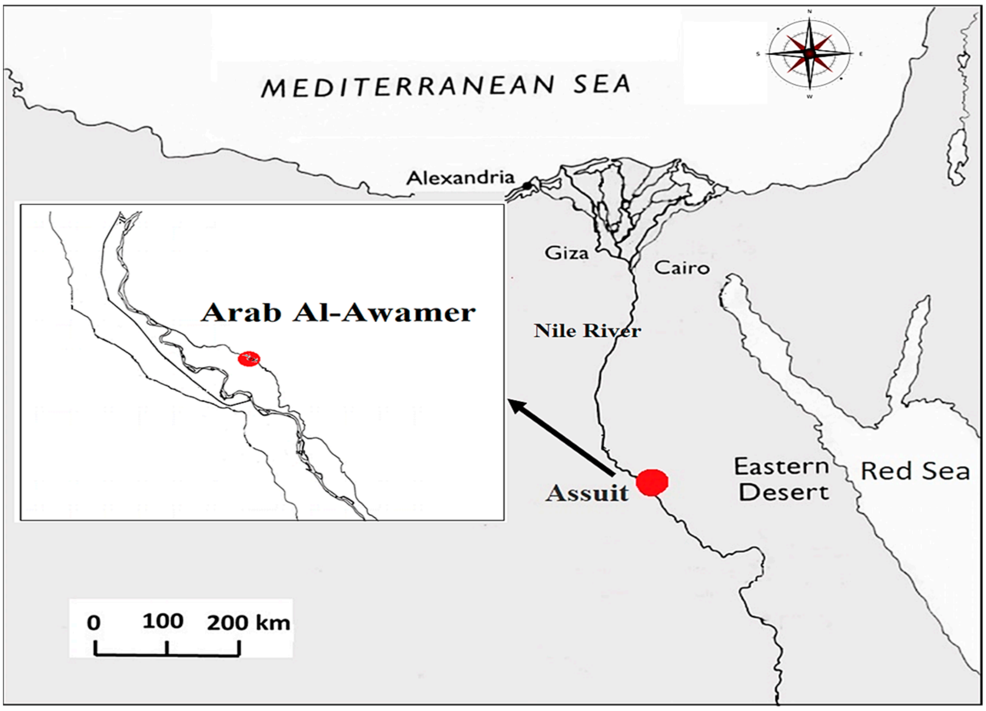

Figure 1. A map illustrating the experimental site of Arab El-Awammer. Research Station, Agriculture Research Institute (ARC), Assuit, Egypt.

Table 1. Average monthly meteorological data for the Arab El-Awammer Research Station during the two growing seasons of 2020/2021 and 2021/2022.

Month	Sunshine Hours (h)		Wind Speed (km/h)		Relative Humidity (%)		Min. Temp. (°C)		Max. Temp. (°C)	
	2019/20	2020/21	2019/20	2020/21	2019/20	2020/21	2019/20	2020/21	2019/20	2020/21
December	9	9	15.4	14.3	57.7	53.6	8.1	9.4	21.5	23.6
January	8.9	8.9	16.5	13.5	59.6	58.9	5.5	7.1	18.5	21.4
February	9.7	9.7	17.7	15.9	54.7	57.4	7.4	7.3	21.4	21.6
March	9.9	9.9	19.3	18.6	44.2	43.4	10.8	11.3	26.2	27.1
April	10.3	10.3	18.8	17.1	38	34.4	14.7	15.1	30.6	32

Note(s): Source: Central Lab for Agricultural Climate, Agricultural Research Center, Egypt. Temp.: temperature; Max.: maximum; Min.: minimum.

Table 2. Physical and chemical characteristics of representative composite soil samples from surface layer (0–25 cm) of Arab El-Awammer Research Station.

Chemical Properties									
pH (1:1)	EC dS/m (1:1)	Soluble cations (meq/L)				Soluble anions (meq/L)		Available phosphorus (ppm)	Total nitrogen (%)
		Ca^{++}	Mg^{++}	Na^{+}	K^{+}	CO_3^{-} + HCO_3^{-}	Cl^{-}		
8.31	0.45	1.69	1.25	0.38	0.78	1.99	1.64	7.08	0.015
Physical properties									
Particle size distribution (%)			Texture class	Moisture content (Volumetric %)			O.M (%)	$CaCO_3$ (%)	Bulk density
Sand	Silt	Clay		S. P.	F.C.	W.P.			
91.1	5.7	3.2	Sandy	23.0	10.9	4.5	0.42	29.80	1.60

Note(s): Three replicates were used to determine each measured property of the soil. The values presented in the table correspond to the arithmetic mean of the results obtained from the analysis of both seasons.

2.2. Experimental Design and Treatments

The experiment was a 3 × 4 factorial laid out in a randomized complete block design with three replications per treatment in each year. Irrigation was assigned as the first factor including three regimes (100% ETc, 80% ETc, and 60% ETc), where the monthly amount of water administered during the growing seasons are shown Table 2. Nitrogen fertilizer was assigned as the second factor comprising four levels (75kg N ha^{-1}, 150 kg N ha^{-1}, 225 kg N ha^{-1}, and 300 kg N ha^{-1}). In this experiment, each plot was a 20 m^2 area, with a width of 4 m, containing 4 ridges 100 cm apart, and a length of 5 m. Quinoa seeds were sown by hand on 1 side of each ridge at a depth of 2–3 cm, with hills spaced at 15 cm intervals, then thinned to maintain 2 plants per hill, preserving a plant density of 53 plants m^{-2}. To prevent weed interference, the plots were regularly maintained through manual hoeing.

The field experiment In each of the two growing seasons was conducted with a surface drip irrigation system to provide a targeted water supply to each individual plant. The system was composed of main irrigation lines that were connected to irrigation pipes. Each main line was equipped with a pressure-reducing valve, which was utilized to manage the water pressure within the irrigation system and to regulate water application throughout the growing season. The emitter spacing was 20 cm, with a total of 20 emitters used per m^2. The irrigation practice was performed weekly using a drip irrigation system with a flow rate of 6.0 L/h.

Reference evapotranspiration (ET_0) values were calculated using the FAO Penman–Monteith method [29] using the CROPWAT model (Smith, 1991). The climatic data used for the estimation of ET0 were collected from the Central Lab for Agricultural Climate, Agricultural Research Center, Egypt.

$$ET_0 = \frac{0.408\Delta(Rn - G) + \gamma\left[\frac{900}{T+273}\right]u2(es - ea)}{\Delta + \gamma(1 + 0.34u2)}$$

where ET_0 is the reference evapotranspiration (mm/day), Rn is the net radiation on the crop surface (MJ/m^2 day^{-1}), G is the soil heat flux density (MJ/m^2 day^{-1}), T is the mean daily air temperature at a 2 m height (°C), $u2$ is the wind speed at a 2 m height (m/s), es is the saturation vapor pressure (kPa), ea = actual vapor pressure (kPa), $es - ea$ is the saturation vapor pressure deficit (kPa) where es is the saturated vapor pressure and ea is the actual vapor pressure, Δ is the slope vapor pressure curve (kPa/°C), and γ is a psychrometric constant (kPa/°C).

The crop coefficient (*Kc*) for the quinoa plants was assumed for each irrigation level (Table 3) according to [29] using the following formula:

$$Kc = \frac{ETc}{ETo}$$

where *Kc* = Crop coefficient, *ETc* = Crop evapotranspiration, and *ETo* = Reference evapotranspiration.

Table 3. Crop coefficient (Kc) values for quinoa plants in different water regimes during the two growing seasons under study.

	100% Kc		**80% Kc**		**60% Kc**	
	2019/2020	**2020/2021**	**2019/2020**	**2020/2021**	**2019/2020**	**2020/2021**
December	0.57	0.40	0.46	0.32	0.37	0.26
January	0.76	0.59	0.61	0.47	0.50	0.38
February	0.93	0.91	0.74	0.73	0.61	0.60
March	0.92	0.90	0.73	0.72	0.60	0.59
April	0.35	0.39	0.28	0.31	0.23	0.25
Average	0.71	0.64	0.56	0.51	0.46	0.42

The crop evapotranspiration (*ETc*) for the quinoa plants was assumed for each irrigation level according to [29] using the following formula:

$$ETc = ETo \times Kc$$

where *ETc* = Crop evapotranspiration, *ETo* = Reference evapotranspiration, and *Kc* = Crop coefficient.

The amounts of actual irrigation water administered under each irrigation treatment (Table 4) are determined using the following equation [30]:

$$I.Ra = \frac{ETc + Lf}{Er}$$

where

I.Ra = total actual irrigation water applied mm/interval.
ETc = crop evapotranspiration using CROPWAT model 8.0 [31].
Lf = leaching factor 10%.
Er = irrigation system efficiency.

Water productivity (*WP*):

The *WP* values for different treatments are calculated as follows:

$$WP\left(\frac{kg}{m^3}\right) = \frac{Seed\ yield\left(\frac{kg}{h}\right)}{CU\left(\frac{m^3}{h}\right)}$$

2.3. Cultural and Cropping Practises

In both seasons, maize (*Zea mays* L.) was the preceding crop. During soil preparation, phosphorus and potassium sources, specifically 90 kg P_2O_5 and 115 kg K_2O per hectare, were applied. To supply the nitrogen fertilizer, ammonium nitrate (NH_4NO_3, 33.5% N) was applied in four equal doses, with the initial dose applied four weeks after the planting date and subsequent doses administered every two weeks as an irrigation solution. Nitrogen fertilizer was added in the form of ammonium sulfate (20.5%).

Table 4. Irrigation water applied (m^3/ha) at different growth months of quinoa grown under different irrigation regimes during the two seasons of 2019/2020 and 2020/2021.

	100% ETc		80% ETc		60% ETc	
	2019/2020	**2020/2021**	**2019/2020**	**2020/2021**	**2019/2020**	**2020/2021**
December	510.84	428.808	408.672	343.032	306.504	257.28
January	975	796.488	780	637.2	585	477.888
February	1488.528	1304.424	1190.832	1043.544	893.112	782.664
March	2346.912	2427.24	1877.52	1941.792	1408.152	1456.344
April	1125.768	1236.648	900.6	989.304	675.456	741.984
Total	6447.048	6193.608	5157.624	4954.872	3868.224	3716.16

2.4. Measurement of Plant Growth Traits

Ten randomly selected plants in each plot were tagged and six agronomic traits were recorded. At harvest time, the average height of each plant from the ground to the highest level of the inflorescence was measured and recorded as plant height (PH, cm). The average length of three panicles, selected randomly from each plot, from the base to the tip of the longest branch using a ruler or measuring tape, was determined as the panicle length (PL, cm). All plant parts, except the roots, secondary branches, and leaves were exposed to sunlight for drying and weighed to determine the dry weight/plant (DW, g). A sample of 1000 seeds was obtained from the combined seed of each replication and weighed to calculate the seed weight (SW, g). The total weight of the seeds from each plot was calculated to measure the seed yield (SY, t/ha), while the plant biomass was dried then weighed to calculate the total yield (TY, t/ha).

2.5. Statistical Analysis

Analysis of variance (ANOVA) was performed using the general linear model procedure (PROC GLM) of SAS 9.4 (SAS Institute Inc., Cary, NC, USA). Variances were not significantly homogeneous between the two years (the two seasons of study); thus, the statistical analysis was performed separately each year. Means were compared with Tukey's HSD test and considered significant at $p \leq 0.05$ [32]. GraphPad Prism software for Windows (Version 8.0, GraphPad software Inc., La Jolla, CA, USA) was utilized to create line plots depicting the effects of each water regime at different levels of nitrogen. Statistical software R (R Core Team, 2021, version 4.1.1) was used to create scatter plots exhibiting the pairwise relationships between each pair of studied traits under both water regimes and nitrogen levels using the *ggplot2* package. Additionally, path analysis using the *lavaan* package was conducted to examine the direct effects of the causal variables of plant height, panicle length, dry weight, seed weight, and total yield on the response variable (seed yield).

3. Results

3.1. Effect of Different Nitrogen and Water Levels on the Studied Traits

The analysis of variance shown in Table 5 indicates that nitrogen level, water regime, and water regime × nitrogen level have highly significant effects ($p < 0.001$) on all the studied traits. The performance of the six studied traits under different irrigation regimes and nitrogen levels is shown in Figure 2. The results indicate that plant height is significantly and positively influenced by increasing levels of both water regimes (60, 80, 100% ETc) and nitrogen levels (75, 150, 225, and 300 kg). results also show that the highest plant height value is significantly noted under the 100% ETc condition with 300 kgN fertilization (90.82 cm), followed by 100% ETc with 225 kgN (78.95 cm), whereas the shortest plant height (45.23 cm) was obtained by the 60% ETc treatment with 75 kgN (Figure 2A). For the panicle length, a similar trend was noticed as the more nitrogen level and irrigation water applied, the longer panicle was observed for quinoa plants (Figure 2B). The results show that the maximum panicle length was significantly recorded by the application of 100% ETc with 300 kgN fertilization (58.27 cm), followed by 80% ETc with 225 kgN fertilization (44.07 cm), and 100% ETc with 225 kgN (42.98 cm), while a significant minimum panicle length (18.93 cm) was recorded when 60% ETc with 75 kgN was applied (Figure 2B). In other words, when less irrigation water is applied, a shorter plant height and panicle length are obtained at all nitrogen levels. Additionally, when the same water level was administered, the plant height and panicle length showed significantly decreasing values with decreased nitrogen levels.

As regards the dry weight (Figure 2C), the results show that the differences between the three water regimes is highly significant and different nitrogen levels result in significantly different dry weights for each water irrigation level. The findings also show that the significantly higher values of dry weight are recorded when 100% ETc is applied at 300 kgN (36.14 g), followed by 225 kgN (35.15 g), 150 kgN (28.82 g), and 75 kgN (24.35). The lowest dry weight of quinoa plants (10.9 g) was recorded when less water and nitrogen levels were applied (60% ETc with 75 kgN, Figure 2C). With respect to the yield traits, higher levels of both water and nitrogen resulted in significantly higher values for seed weight, seed yield, and total yield. Generally, the highest values for seed weight, seed yield, and total yield were always obtained when a maximum water amount was applied (100% ETc) and the highest nitrogen level followed (Figure 2D–F). It can be observed that both levels of water (100% and 80% ETc) showed a non-significant difference for seed weight, such as was observed for nitrogen levels of 150 and 225 kgN (Figure 2D). Furthermore, we observed that the total yield levels were higher when 80% ETc was applied with 150 kgN than that recorded at 100% ETc for the same nitrogen levels, while other seed yield values were similar at 80% ETc when 150 kgN was used. Seed weight recorded at the maximum value when 100% ETc was applied in a combination with 225 kgN (23.16 g); the lowest seed weight (3.86 g) was observed by the combined application of 60% ETc and 75 kgN (Figure 2D). Additionally, the highest seed yield (1.65 t/ha) was obtained by combining the application of both 100% ETc with 300 kgN, followed by the combined application of 100% ETc with 225 kgN (1.32 t/ha); the lowest seed yield (0.50 t/ha) was recorded under the lowest average water and nitrogen levels applied (Figure 2E). For the total yield, the highest (3.79 t/ha) and lowest (1.01 t/ha) levels were noted under the combined application of 100% ETc with 300 kgN and 60% ETc with 75 kgN, respectively (Figure 2F).

To confirm such results, a heatmap was presented to highlight the impact of different treatment combinations on the measured characters in the present study (Figure 2G). For all traits of study, the combined application of 100% ETc with 300 kgN, followed by 80% ETc with 225 kgN, resulted in the highest values for plant height, panicle length, dry weight, seed weight, seed yield, and total yield. In contrast, it was observed that the combination of a 60% ETc and 75 kgN application resulted in the lowest values for all of the aforementioned traits.

Table 5. Statistical analysis of six agronomic and yield traits of quinoa as affected by different irrigation regimes and nitrogen levels for both growing seasons (2020/21 and 2021/22) at Arab El-Awammer Research Station.

Source of Variance	Plant Height (cm)		Panicle Length (cm)		Dry Weight (g)		Seed Weight (g)		Seed Yield (t/ha)		Total Yield (t/ha)	
	2020/21	2021/22	2020/21	2021/22	2021/22	2020/21	2021/22	2020/21	2021/22	2020/21	2021/22	2020/21
Water regimes (WR)	1193.50 ***	1306.10 ***	777.29 ***	782.43 ***	1100.79 ***	919.34 ***	385.66 ***	285.78 ***	86,918.52 ***	93,395.54 ***	1,102,920.08 ***	920,875.63 ***
Nitrogen level (NL)	902.64 ***	1024.65 ***	575.05 ***	673.50 ***	44.81 ***	82.93 ***	90.31 ***	55.29 ***	129,969.23 ***	154,889.98 ***	589,359.65 ***	786,252.82 ***
WR × NL	55.75 ***	45.35 ***	77.19 ***	76.88 ***	28.33 ***	41.18 ***	14.02 ***	21.68 ***	11,597.06 ***	12,345.87 ***	22,062.73 ***	110,091.25 ***
CV	19.71	20.00	30.94	30.70	32.00	33.50	33.80	35.20	35.80	36.40	35.20	36.80
SD	12.46	13.08	10.40	10.79	8.47	8.21	5.72	4.98	135.33	144.74	344.14	384.42
SE	2.10	2.18	1.73	1.80	1.41	1.37	0.95	0.83	22.60	24.12	57.35	64.10

Note(s): CV: coefficient of variation, SD: standard deviation, SE: standard error. ***, indicate a statistically significant difference at p-value < 0.001.

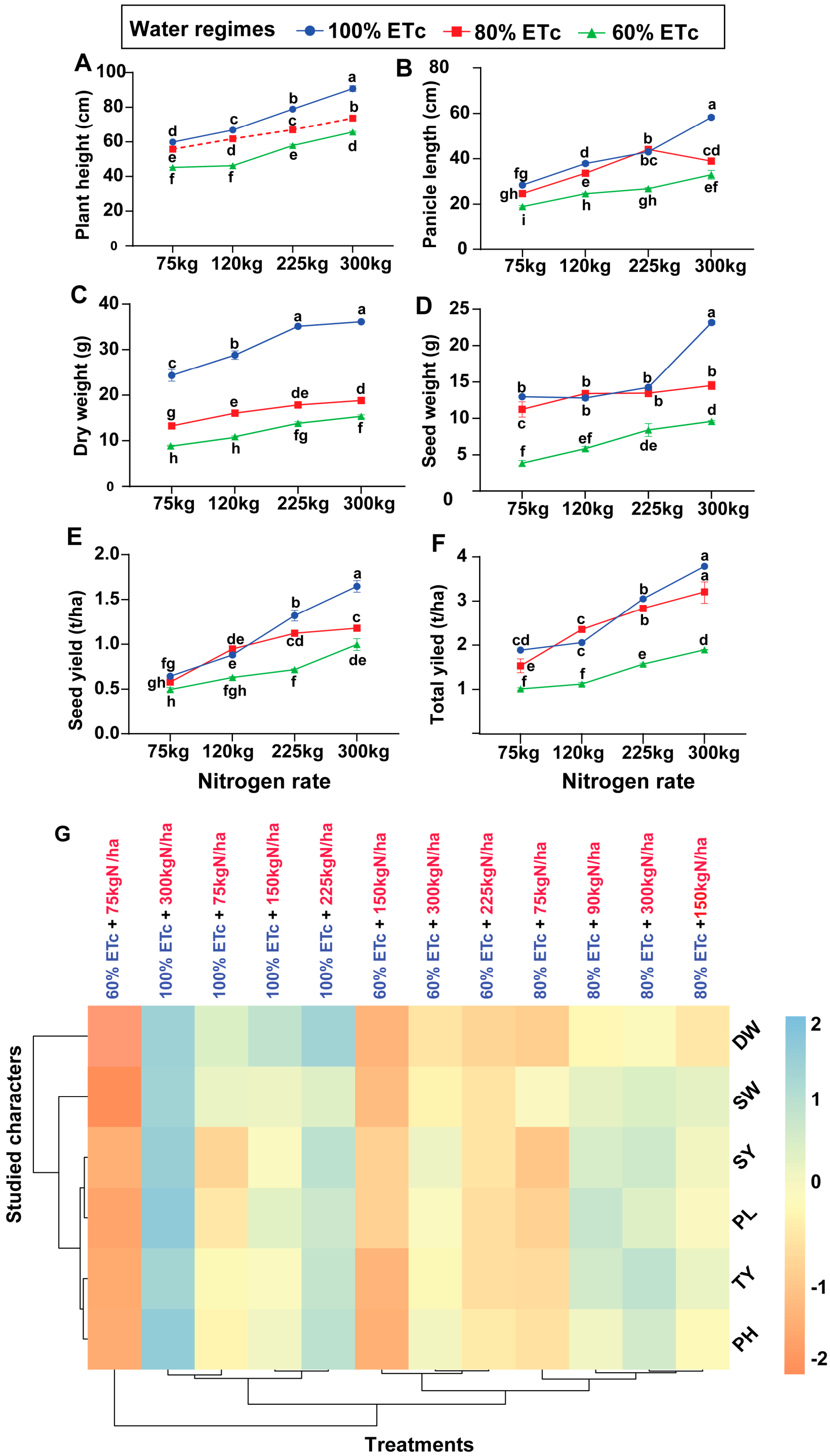

Figure 2. Line plots showing the effects of different nitrogen levels under various water regimes on plant height (cm) (**A**), panicle length (cm) (**B**), dry weight (g) (**C**), seed weight (g) (**D**), seed yield (t/ha) (**E**), and total yield (t/ha) (**F**) of quinoa, averaged among the two growing seasons of 2020/21 and 2021/22 at Arab El-Awammer Research Station. A heatmap showing the performance of each studied trait with different combinations of both water regimes and nitrogen levels (**G**). PH: plant height; EL: panicle length; DW: dry weight; SW: seed weight; SY: seed yield; TY: total yield. Different lowercase letters in the figure indicate significant treatments.

3.2. Relationships among Studied Traits as Affected by Three Water Regimes

The results of the scatter plot presented in Figure 3 exhibit the pairwise relationships between each of the two studied traits as affected by three water regimes. These findings reveal that most of the pairwise relationships are positive and significant ($p < 0.01$). In particular, the investigation revealed that seed yield exhibited a significant correlation with several other traits, with the highest correlation coefficient being observed for plant height (r = 0.99) under the 100% ETc treatment. Additionally, under the 60% ETc treatment, panicle length (r = 0.97) and seed weight (r = 0.95) demonstrated a notable correlation to seed yield, while the dry weight (r = 0.99) was observed to be the most strongly correlated trait under the 80% ETc treatment. Regarding the association between plant height and other traits, the investigation showed that the strongest correlation coefficients were observed for panicle length (r = 0.98) under the 100% ETc treatment, dry weight (r = 0.96) under the 80% ETc treatment, seed weight (r = 0.96) under the 60% ETc treatment, and total yield (r = 0.99) under the 60% ETc treatment. In terms of the panicle length, the investigation determined that the most notable correlation coefficients were observed for dry weight (r = 0.91) under the 80% ETc treatment, seed weight (r = 0.85) under the 80% ETc treatment, and total yield (r = 0.95) under the 100% ETc treatment. At the 80% ETc level, the most significant correlation coefficients between dry weight and other traits were observed for seed weight (r = 0.85) and total yield (r = 0.99).

3.3. Relationships among Studied Traits as Affected by Four Nitrogen Levels

The results of the scatter plot in Figure 4 show the pairwise relationships between the studied traits as affected by four different nitrogen levels. Most of the pairwise relationships between the studied traits were significantly positive ($p < 0.01$). Furthermore, there were no negative correlations observed among any of the studied traits. According to the findings, the strongest correlation coefficients can be observed between seed yield and panicle length (r = 0.99), dry weight (r = 0.98), seed weight (r = 0.98), and plant height (r = 0.98) at 300 kgN. At the highest nitrogen level, there was a highly significant positive association between plant height and all the other studied traits. The strongest correlation coefficients were observed between plant height and panicle length (r = 0.99) and dry weight (r = 0.98) at 300 kgN, seed weight (r = 0.98) at 225 kgN, and total yield (r = 0.98) at 300 kgN. The findings reveal that the highest correlation coefficients for panicle length can be observed for dry weight (r = 0.99) and seed weight (r = 0.98) at 300 kgN, and with total yields (r = 0.98) at both 75 and 225 kgN. Concerning the association to dry weight, the highest correlation coefficients were observed for seed weight (r = 0.98) and total yield (r = 0.80) at 300 kgN. Furthermore, for the relationship between seed weight and total yield, the correlation coefficient presented the highest value (r = 0.98) at 300 kgN.

3.4. Path Analysis under Different Water Regimes and Nitrogen Levels

Figure 5 presents the results of the path analysis performed in this investigation to examine the direct and indirect impacts of the various studied traits on seed yield, the response variable, under different water regimes. The direct path coefficients for each independent variable on the dependent variable (seed yield) at the water treatment value of 100% ETc were 0.63, 0.13, 0.07, −0.12, and 0.28; at 80% ETc these were −0.17, 0.17, 0.71, 0.16, and 0.17, and at 60% ETc these were −0.88, 0.82, 0.76, 0.82, and 0.78 for plant height, panicle length, dry weight, seed weight, and total yield, respectively. Based on the path diagram, it is evident that the majority of the direct path effects are positive and statistically significant. These effects were most pronounced under the 60% ETc water regime, with the strongest effects observed for panicle length, followed by seed weight, total yield, and dry weight on seed yield. For the 80% Etc treatment, dry weight still had a positive and significant effect; for the 100% ETc treatment, only plant height followed by total yield showed a highly significantly positive direct effect on the seed yield, implying that such traits could be used as markers for direct selection to improve the seed yield.

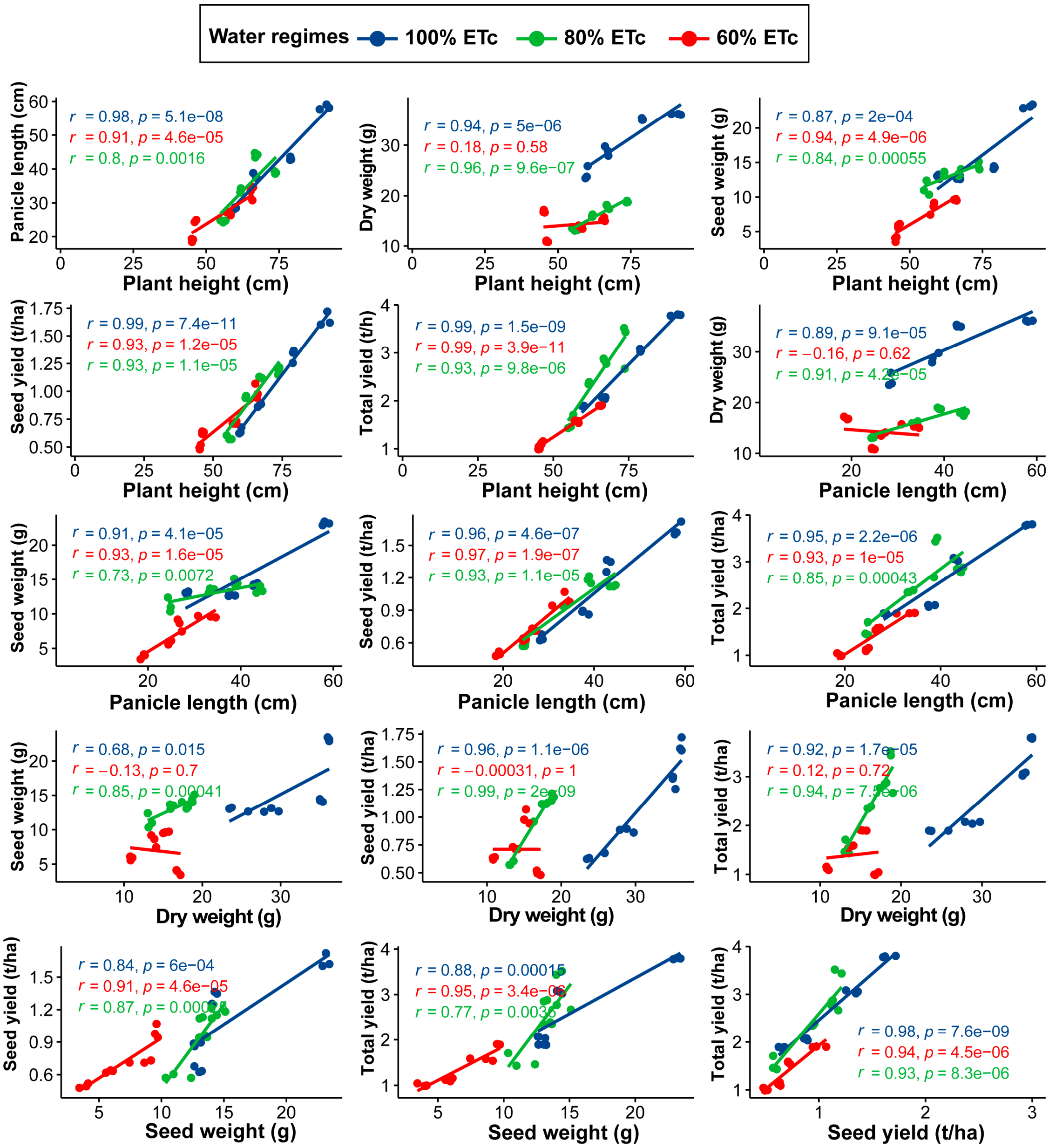

Figure 3. Scatter plot showing the pairwise relationships between six studied quinoa traits under three water regimes (60%, 80%, and 100% ETc) averaged over the two seasons of study at Arab El-Awammer Research Station. Correlation coefficients (*r*) and *p*-values are shown in the upper-left corner of the plot.

A path analysis was also performed at different nitrogen levels, as indicated in Figure 6. As the causal factors influencing the seed yield (response variable), five direct coefficients were determined, including plant height, panicle length, dry weight, seed weight, and total yield under each nitrogen level in the study. These five direct path coefficients were 0.92, 0.65, 0.25, −0.78, and −0.84 at 75 kgN; 0.49, −0.16, −0.25, 0.68, and 0.17 at 150 kgN; 0.86, 0.72, −0.44, −0.28, and −0.38 at 225 kgN; and 0.13, 0.81, −0.11, 0.16, and 0.01 at 300 kgN, for plant height, panicle length, dry weight, seed weight, and total yield, respectively. The path diagram further exhibits that the direct path coefficient values vary due to the application of different nitrogen levels, showing both significant positive and negative path coefficients. The findings also show that seed yield is positively, directly affected by plant height (0.92 **) at and (0.86 **) at 225 kgN. Moreover, seed yield was highly and directly, but negatively, affected by seed weight (−0.84 ** and −0.78 **) at 75 kgN.

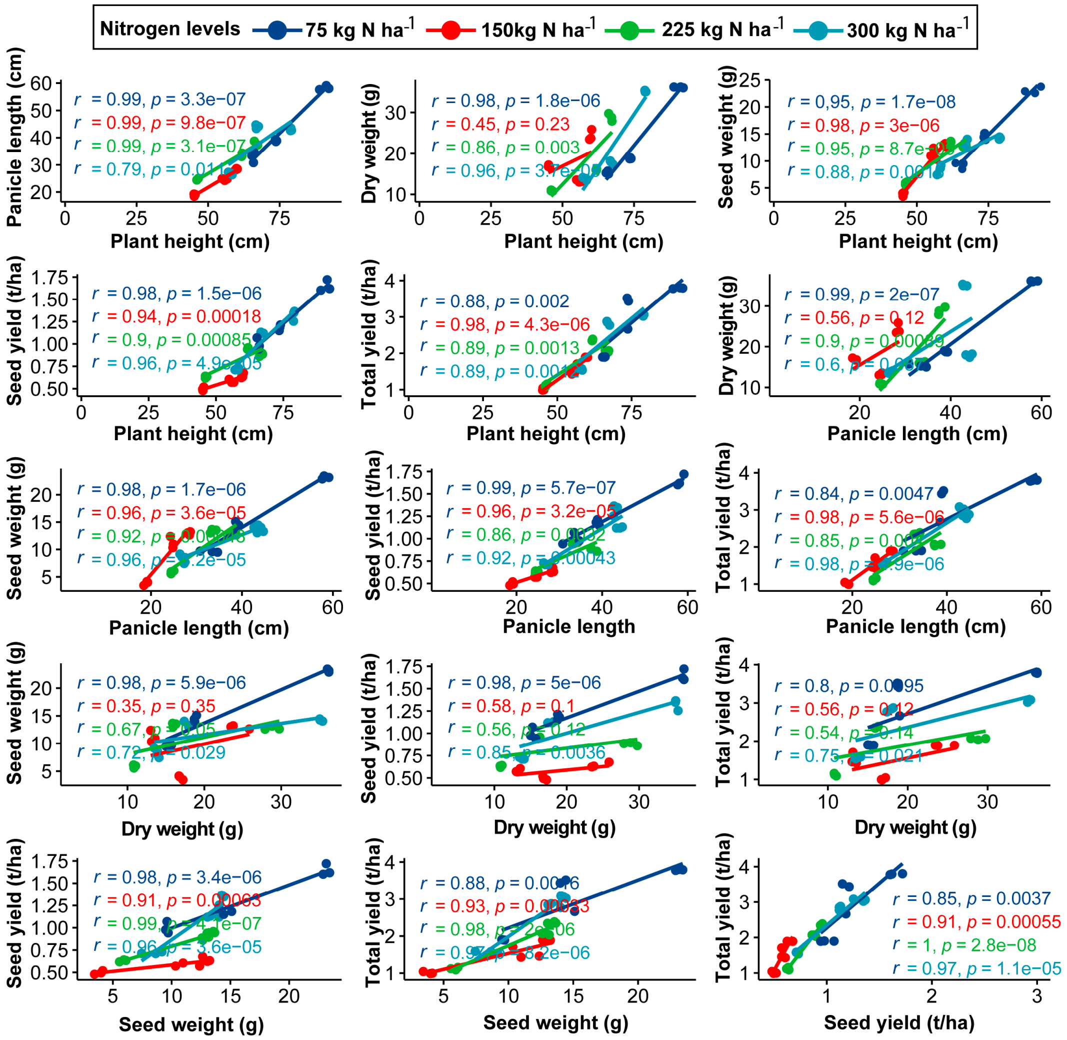

Figure 4. Scatter plot showing the pairwise relationships between six studied quinoa traits under four nitrogen levels (75, 150, 225, and 300 kgN ha^{-1}) averaged over the two seasons of study at Arab El-Awammer Research Station. Correlation coefficients (*r*) and *p*-values are shown in the upper-left corner of the plot.

3.5. Effect of Water Regimes and Nitrogen Levels on Water Productivity Levels

The results provided in Table 6 show the water productivity levels of different water regimes (100% ETc, 80% ETc, and 60% ETc) combined with four nitrogen levels (75, 150, 250, and 300 kgN ha^{-1}). The results indicate that the water productivity of quinoa plants is noticeably affected by both water regime and nitrogen level. It was observed that as the water regimes decrease from 100% to 60%, water productivity increases for all nitrogen levels. This indicates that water use efficiency improves with lower ETc levels. However, for the 80% ETc regime, the increase in nitrogen levels has a greater influence on water productivity than for the other regimes. This implies that, with a restricted water supply, an adequate nitrogen supply is crucial for achieving optimal water productivity. In terms of the water regime's overall impact on water productivity at all nitrogen levels, the highest productivity was recorded at 80% ETc (0.58 kg/m^3), followed by 100% ETc (0.54 kg/m^3) and 60% ETc (0.52 kg/m^3). This suggests that reduced irrigation can improve the water productivity of quinoa plants. Additionally, as the nitrogen level increases from 75 to 300 kg/ha, water productivity also increases during all water regimes. The highest water productivity can be observed at a nitrogen level 300 kg/ha for 60% ETc and 80% ETc regimes, where water productivity is 0.73 and 0.71 (kg/m^3), respectively.

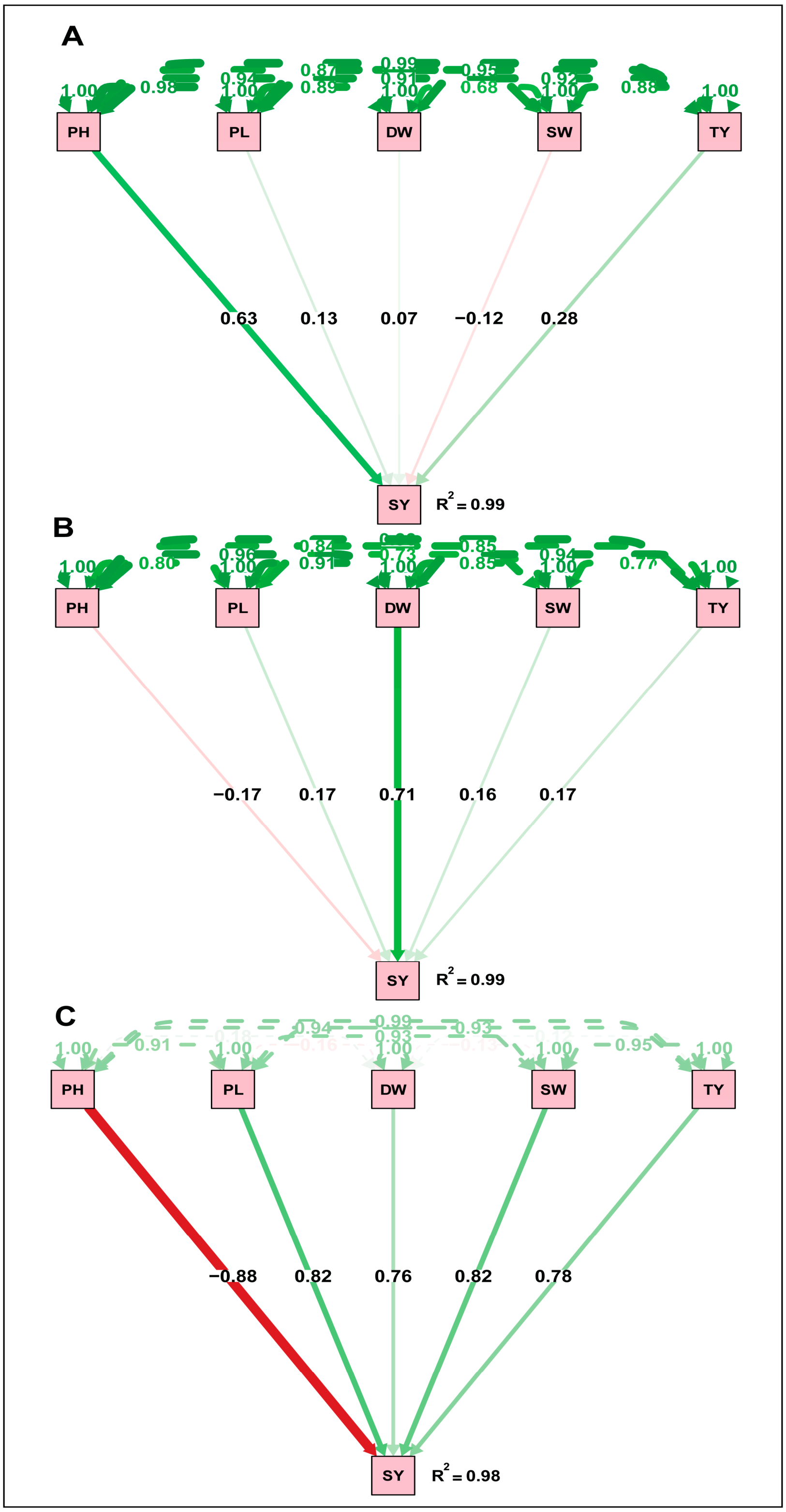

Figure 5. Path analysis diagram showing the interrelationships between seed yield (response variable) and other studied traits under three water regimes: 100% (**A**), 80% (**B**), and 60% ETc (**C**). Bidirectional arrows show the correlation between the variables and single-headed arrows indicate direct path coefficients; green and red arrows represent positive and negative effects, respectively. Solid arrows indicate $p < 0.05$. PH: plant height (cm); EL: panicle length (cm); DW: dry weight (g); SW: seed weight (g); SY: seed yield (t/ha); TY: total yield (t/ha).

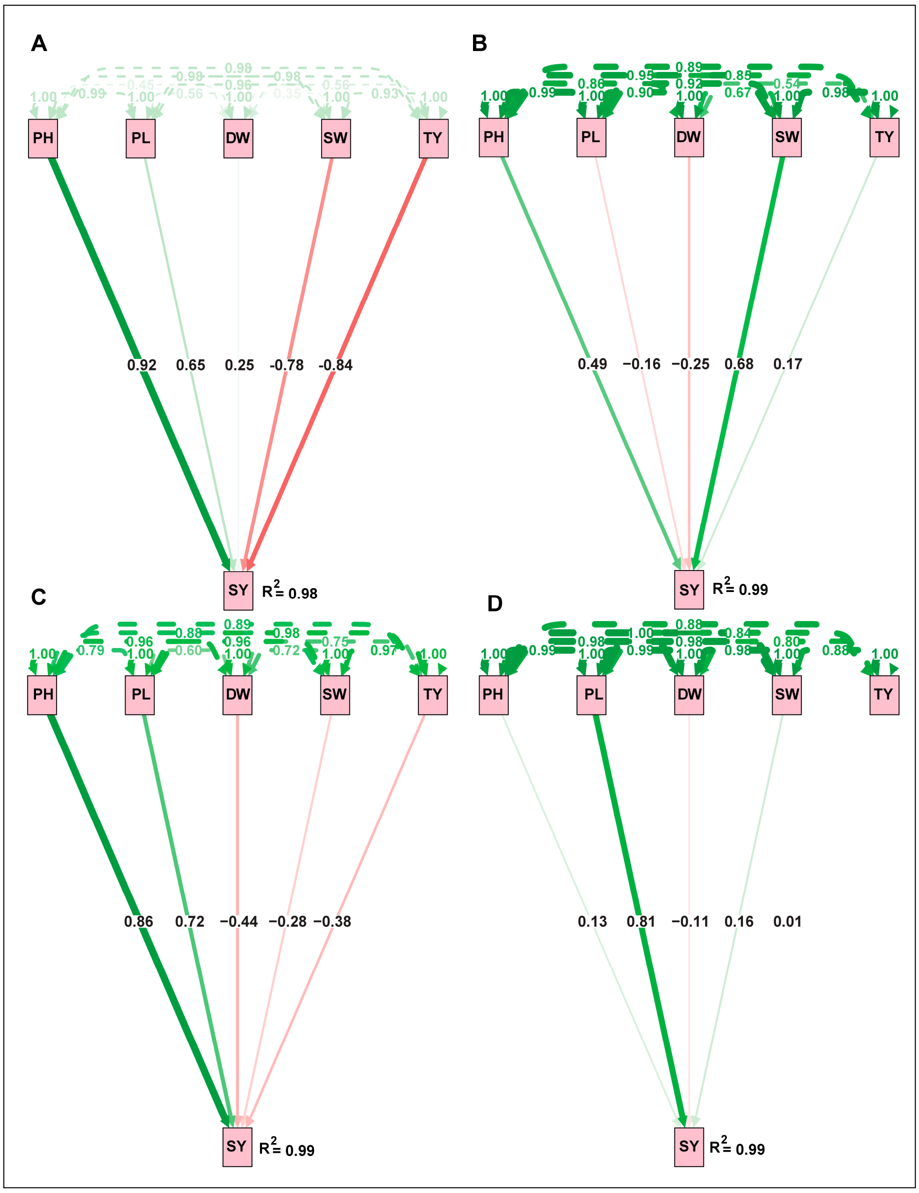

Figure 6. Path analysis diagram showing the interrelationships between seed yield (response variable) and other studied traits under four nitrogen levels of 75 (**A**), 150 (**B**), 225 (**C**), and 300 kgN ha^{-1} (**D**). Bidirectional arrows show the correlation between the variables and single-headed arrows indicate direct path coefficients; green and red arrows represent positive and negative effects, respectively. Solid arrows indicate $p < 0.05$. PH: plant height (cm); EL: panicle length (cm); DW: dry weight (g); SW: seed weight (g); SY: seed yield (t/ha); TY: total yield (t/ha).

Table 6. Water productivity during different water regimes and nitrogen levels.

Water Regime	Nitrogen Level	Water Productivity
100% ETo	75 kgN ha^{-1}	0.31
100% ETo	150 kgN ha^{-1}	0.43
100% ETo	225 kgN ha^{-1}	0.64
80% ETo	75 kgN ha^{-1}	0.35
80% ETo	150 kgN ha^{-1}	0.57
80% ETo	225 kgN ha^{-1}	0.68
80% ETo	300 kgN ha^{-1}	0.71
60% ETo	75 kgN ha^{-1}	0.37
60% ETo	150 kgN ha^{-1}	0.46
60% ETo	225 kgN ha^{-1}	0.53
60% ETo	300 kgN ha^{-1}	0.73

4. Discussion

The results of the present study indicate a significant reduction in various agronomic and yield attributes resulting from reduced irrigation water usage. This is consistent with the results of previous studies on quinoa [11,33–35] and other field crops, such as maize [36,37], soybean [38,39], barley [40,41], wheat [42,43], and rice [44,45]. Overall, the present study's results demonstrate that plant height and panicle length exhibit an increasing trend, with increasing levels of both nitrogen and irrigation water during the growing seasons. Meanwhile, medium levels of irrigation water and nitrogen recorded medium values for both traits.

4.1. Influence of Water Regimes and Nitrogen Levels on Quinoa's Agronomic and Yield Traits

Interestingly, the study revealed that, during a specific water regime, there was a significant increase in quinoa plant height and panicle length with increased nitrogen levels. This suggests the enhancing and additive effect of nitrogen application, particularly when 300 kg of nitrogen was applied during any of the three water regimes. The results suggest that nitrogen may have helped to maintain yields numbers under constrained water conditions. Previous studies have also confirmed similar results [15,16,19,46]. The study also observed the positive effect of nitrogen on plant height, panicle length, and dry weight. The response showed the remarkable increasing trend and positive linear response of quinoa plants to nitrogen, especially with the increasing water levels provided during the growing season. This response can be explained by the positive effect of nitrogen doses on the dry matter and biomass enhancement of quinoa plants [19].

The results of our study show that seed weight and yield have a positive growing trend when nitrogen is applied, improving these traits during any of the water regimes. Notably, at the same water level, nitrogen application significantly enhanced seed weight, particularly when 300 kg was provided at 100% ETc. While a previous investigation on winter wheat indicated that nitrogen increased the yield when water availability was only modest [25], our study determined that nitrogen applied during severe water-shortage or optimal water conditions may aid in preserving seed yield and weight, thus reducing the productivity gap between contrasting water scenarios. In addition, our present findings demonstrate that nitrogen is a greater limiting factor than water in respect to achieving a high seed yield. Furthermore, despite the few fluctuations evident, the total yield of quinoa plants responded in a positive, linear manner, particularly at a water level of 60% ETc. Collectively, it may be argued that providing quinoa plants with increasing nitrogen doses may have provided the quinoa with some degree of adaptability to water-shortage conditions, leading to crop recovery and, thereby, maintaining yields. Regardless of such a compensatory effect of adding extra nitrogen to the plants, previous studies [47,48] have been found to be consistent with those indicated in the present study, as they reported that drought greatly decreased seed yield and its attributes in comparison to plants that were adequately irrigated. Generally, according to our results, in the present study, 300 kg N ha^{-1} could be applied to achieve the best quinoa production rates under optimal irrigation conditions (100% ETc) and 300 kg N ha^{-1} at 80% ETc.

4.2. The Impact of Different Water Regimes on the Correlations between the Investigated Characteristics

The study of correlation is an important step in developing a breeding program for quinoa [36,49]. In addition, identifying the best traits correlating to grain yield could be a useful method to help breeders screen for suitable attributes, conferring better performances under limited water resources and lower nitrogen inputs for quinoa [50].

The correlation coefficients for most of the trait pairs were mostly positive and significant during each of the three water regimes, which means that different water scenarios resulted in similar responses for the studied traits. It would also mean that different water conditions did not affect the trends of traits differently. Similar results were reported in previous investigations [49,51–54]. Importantly, the association between seed yield and each of the other studied traits in our study indicated strong correlations, which were observed for plant height, panicle length, dry weight, seed weight, and total weight. Furthermore, this indicated the suitability of these attributes as selection criteria, which could help plant breeders achieve high seed yields, even under limited water conditions. Al-Naggar et al., 2017 [49] analyzed the correlation coefficient between quinoa seed yield and thousand-grain weight and revealed strong positive-correlation coefficients (r = 0.81, 0.86, and 0.96) under good watering, water stress, and severe water stress conditions, where the field capacity values were about 95, 65, and 35%, respectively. In addition, the strong and positive associations noticed between the seed yield and plant height and panicle length in the present study were also revealed by [55] when they screened the performance of quinoa plants under three deficit-irrigation conditions of 0.80, 0.55, and 0.30%. A previous investigation also reported highly significant and positive correlation coefficients between the panicle length and seed yield of quinoa [56], suggesting that a longer panicle would result in a higher grain yield. According to the relationship between plant dry weight and seed yield, the results of the present study are also in line with those reported by [19], as they reveal that, with an increasing water quantity, especially with an increasing level of applied nitrogen, both the dry weight and seed yield of quinoa plants also increase.

4.3. The Impact of Different Nitrogen Levels on the Correlations between the Investigated Characteristics

The study considered the potential impact of different levels of nitrogen applied on the relationships among the agronomic traits, specifically the correlation between the seed yield and other traits analyzed. The results indicate a strong and positive correlation between each pair of traits across all levels of nitrogen inputs, including low, medium, and high levels. These results are in accordance with those obtained for other investigations [50,57,58]. These results demonstrate that changes in nitrogen levels have a similar effect on the relationships among the studied traits, particularly the correlation between the seed yield and other traits. However, the estimation of various nitrogen levels affecting barley showed a negative correlation between the grain weight and yield [50,59].

4.4. Exploring Variables' Causal Effects on Seed Yield under Different Water and Nitrogen Treatments

Path analysis is an important tool for understanding the correlation coefficients between agronomic parameters and their direct and indirect effects, as it can be used to verify cause-and-effect relationships [50]. A path analysis was performed in the present study to investigate the causal effects of multiple studied variables, including both the direct and indirect effects, on the seed yield during different water regimes and under different nitrogen levels [50,60–62]. The path analysis used in this study showed high determination coefficients across all three water regimes and four nitrogen application levels, indicating the reliability of the model and its usefulness in analyzing the relationships between the studied traits. The study's results also exhibit a high, positive, direct effect between all the studied variables on the seed yield, except for seed weight at 100% ETc and plant height at 60 and 80% ETc. These results highlight that the studied agronomic traits, such as dry weight, panicle length, and total yield, have a positive linear contribution to the final seed yield [63]. For the two restricted water conditions, the plant's height may indicate that a shorter plant results from the application of less water, which consequently as an adverse effect on the seed yield. However, under optimal water conditions, plant height exhibited the most substantial positive, direct influence on the seed yield [53,63]. The findings of Bhargava et al. [63], in contrast, showed that seed weight had a positive, direct effect on the seed yield.

The path analysis conducted in the present study using varying nitrogen levels revealed inconsistent findings, as a strong, negative, direct effect was observed for the seed weight and total yield under a low nitrogen input. In contrast, these traits had a positive effect when administered a high nitrogen level. Similar results were reported by [64], where they indicated that maize grain weight, in low-nitrogen conditions, showed a significant, negative, direct effect on the seed yield. Furthermore, the lower direct path coefficient values at high nitrogen levels might have been due to the quinoa plants tending to have a similar performance when administered a high amount of nitrogen, which was inconsistent with the result of previous studies [65]. Additionally, in contrast to the effects of different water levels, plant height exhibited a significant, positive, direct effect under all three low-nitrogen levels, highlighting the crucial role of this trait under conditions of limited nitrogen availability. In general, based on the results of the path analysis, the most effective approach to evaluate seed yield would be to prioritize the selection of traits that demonstrate a strong, positive, direct effect under low-nitrogen levels.

4.5. The Impact of Varying Water and Nitrogen Levels on the Water Efficiency of Quinoa

The results for water productivity in the present investigation illustrate that, as nitrogen levels increase from 75 to 300 kg/ha, water productivity generally increases across all water regimes. This suggests that optimizing nitrogen management practices is crucial for improving water use efficiency and crop yield in agriculture. Such increases in the seed yield and water productivity of quinoa, in response to increasing nitrogen rates, can be primarily attributed to the stimulation of metabolic activity by nitrogen. This, in turn, leads to an increase in the number of metabolites, which are predominantly utilized for yield production and its components. These findings are corroborated by the works of various researchers [66]. The results show that as the ETc level decreases from 100% to 60%, water productivity generally increases for all nitrogen levels. This implies that using regulated deficit irrigation can be an effective strategy for improving water productivity and crop yield in areas where water resources are scarce. However, the impact of water regimes on water productivity is not uniform for all nitrogen levels. For instance, at 80% ETc, the impact of nitrogen levels on water productivity is more significant than during other water regimes. This suggests that a balanced approach to water and nitrogen management is necessary to achieve optimal water productivity levels. The data also highlight the importance of considering the interplay between water regimes and nitrogen levels when optimizing water productivity. For instance, the best water productivity level is observed with 300 kg/ha of nitrogen for 60% ETc. This suggests that a combination of optimal nitrogen management practices and regulated deficit irrigation can result in higher water productivity levels. Furthermore, the results suggest that improving irrigation efficiency can also play a critical role in improving water productivity. Efficient irrigation practices can help reduce water consumption levels and improve crop yields, thereby increasing water productivity.

5. Conclusions

The present study investigated the effects of varying levels of water and nitrogen fertilizer on the agronomic and yield traits of quinoa (cv. Q-36). The results show that the nitrogen level and irrigation regime, and interaction between the two, significantly affects all the traits studied, including plant height, panicle length, dry weight, seed weight, seed yield, and total yield. The correlation and path analyses were influenced by various water regimes and nitrogen levels, as different strong correlation and direct effect coefficients were observed among different water scenarios and nitrogen levels. These results can be utilized to optimize quinoa cultivation under conditions of water scarcity and limited nitrogen availability and provide an insight into the effects of these conditions on quinoa growth and yield. To conclude, the results of our study demonstrate that the application of nitrogen can have a significant impact on the yield traits of quinoa, particularly when applied at a rate of 300 kg per 100% ETc. Moreover, we also identified that the application of nitrogen during either severe water scarcity or optimal water conditions can help to maintain a high seed yield, ultimately reducing the productivity gap under different water scenarios. The water productivity level in this study tended to increase with the increasing nitrogen rates, ranging from 75 to 300 kg/ha, across all water regimes. These observations underscore the significance of optimizing nitrogen management techniques to enhance water use efficiency and crop yields for quinoa. Ultimately, optimizing nitrogen management practices using regulated deficit irrigation methods, improving irrigation efficiency, and incorporating drought-tolerant crops can all play a critical role in improving water productivity and crop yield. These findings can help inform agricultural practices and policies aimed at improving water use efficiency and sustainability. Based on the results of the present study, some potential areas for the future research can include:

1. Investigation into the molecular and physiological mechanisms that underlie the effects of water and nitrogen fertilizer on quinoa growth and yield.
2. Development of new and improved cultivars of quinoa that are better adapted to challenging growing conditions, such as drought and low nitrogen availability.
3. Investigation into the nutritional composition of quinoa under different water and nitrogen fertilizer regimes, to determine the effects on its quality as a food crop.
4. Comparison of the environmental impacts of different quinoa cultivation practices, including the use of water and nitrogen fertilizers, to identify sustainable practices for the production of quinoa.

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