

Investigating the quality of quinoa (*Chenopodium quinoa* Willd.) seed under the influence of different levels of irrigation and vermicompost

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Abstract

Quinoa (*Chenopodium quinoa*), a globally sought-after crop for its nutritional value and adaptability, faces increasing demands for sustainable cultivation practices. This two-year study, conducted at the Research Farm of the University of Kurdistan, Iran (2021–2022), investigated the impact of varying irrigation levels and vermicompost application on quinoa yield and seed quality, aiming to reduce chemical fertilizer dependency. The experiment utilized a split-plot based on a randomized complete block design. Four irrigation levels (50%, 75%, 100%, and 125% of quinoa's water requirement) constituted the main factor, while four vermicompost application rates (0, 5, 10, and 15 tons per hectare) formed the sub-factor. The results showed that the 125% water requirement treatment achieved the highest seed yield ($2131.51 \text{ kg ha}^{-1}$) and biological yield ($4975.10 \text{ kg ha}^{-1}$), while the 15 tons per hectare vermicompost application resulted in significant yield improvements, reaching $1784.01 \text{ kg ha}^{-1}$ for seed yield and $4100.25 \text{ kg ha}^{-1}$ for biological yield. Notably, the highest nitrogen concentration (2.54%) in quinoa seed was observed in the second year with 15 tons per hectare of vermicompost and 50% of the water requirement. Furthermore, the application of 15 tons per hectare of vermicompost led to a 54% increase in phosphorus, 51% increase in potassium, and a 23.79% increase in seed calcium compared to the control treatment. This study highlights the potential of vermicompost and optimized irrigation levels to significantly enhance quinoa yield and improve the nutritional profile of quinoa seeds. These findings promote sustainable agricultural practices by minimizing reliance on chemical fertilizers while optimizing resource utilization.

Introduction

Quinoa (*Chenopodium quinoa* Willd), a pseudocereal belonging to the Amaranthaceae family (Ocampo et al., 2023), has gained global recognition for its nutritional value and versatility. Quinoa seeds, a rich source of antioxidants, essential amino acids, and gluten-free, are widely consumed for human nutrition (FAO 2013). Quinoa flour is used in baking bread, soups, and pasta, while young leaves serve as fresh or cooked vegetables (Chen et al. 2023). One of quinoa's significant strengths lies in its protein content, ranging from 14–20%. This complete and balanced vegetable protein not only aids in growth and development but also provides energy, making it a particularly beneficial food source for vegetarians (Chen and Liao 2022). Quinoa is also a good source of calcium, gluten-free, easily digestible (Lilian 2019), and suitable for individuals with lactose intolerance. It provides a comprehensive range of essential amino acids, including lysine, isoleucine, leucine, phenylalanine, tyrosine, threonine, tryptophan, valine, histidine, and methionine (Morita et al. 2001). Its protein quality surpasses that of many other seeds (Vega-Gálvez et al. 2010), with higher lysine and amino acid content compared to wheat. Quinoa also contains higher levels of calcium (Ca), phosphorus (P), and iron (Fe) compared to maize (Jan et al. 2023). Beyond its nutritional benefits, quinoa boasts antioxidant, anti-cancer, anti-inflammatory, hypoglycemic, lipid-lowering properties, and potential for weight management. Consequently, quinoa offers a valuable means to improve overall nutritional status and potentially prevent various diseases (Jan et al. 2023; Ren et al. 2023).

In the face of water scarcity, deficit irrigation has emerged as a promising strategy to optimize crop yield using available water resources (Geerts and Raes 2009). High-efficiency irrigation systems like drip irrigation enhance water productivity, promote sustainable development in agriculture, and contribute to water conservation (Liu et al. 2018). Efficient water management directly impacts plant yield and productivity. The drip irrigation method, by delivering water directly to the root zone, reduces surface evaporation and deep-water penetration, leading to increased crop yields (Valentín et al. 2020). Organic matter plays a crucial role in enhancing soil properties, particularly in arid and semi-arid regions. The type, amount, and size of organic matter significantly affect soil properties and crop yields (Li et al. 2019; Celestina et al. 2019). Vermicompost, a nutrient-rich organic fertilizer produced through the decomposition of organic waste by earthworms and microorganisms, provides essential nutrients for plant growth (Chandra 2015). Vermicompost enhances root cell membrane permeability, stimulates root growth, and promotes the growth of root hairs, resulting in increased nutrient uptake by plants (Chandra 2015).

Vermicompost is rich in nutrients that are readily available to plants, such as nitrates, phosphorus, potassium, calcium, and magnesium. It contains 40–60% more humic compounds compared to regular compost, making it more efficient (Jabeen and Ahmad 2019). Studies have shown that organic fertilizers have a significant impact on plant growth and yield, with an estimated effect of 60% in the first year, and 45%, 30%, and 25% in the second, third, and fourth years respectively (Tantawy et al. 2009). In a study conducted by Chen and Liao (2020) on seven varieties of quinoa, it was found that Taiqi black quinoa is rich in protein, high in dietary fiber, and low in fat, making it suitable for weight-loss purposes. Taiqi White Quinoa and Shangri-La Red Quinoa exhibited superior essential amino acid content, making them more suitable for infants and young children. On the other hand, Shangri-La Black Quinoa demonstrated high potassium levels and low sodium levels, making it a suitable choice for middle-aged and elderly individuals. Chen et al. (2023) provided a detailed evaluation of the nutrient composition of thirty different varieties of quinoa seeds, including soluble protein, soluble sugar, amino acids, vitamins, fatty acids, and saponin, highlighting the diverse nutritional benefits. Considering the importance of quinoa as a valuable seed and its adaptability to different weather conditions, conducting a study in Iran to assess the quality of quinoa seeds as a low-expectation product would be a strategic initiative.

Materials and methods

Site description

The present research was conducted in the Agricultural Research Field, located in Dehgolan Plain (18° 35' N and 18° 47' E and an altitude of 1866 m above sea level) at Kurdistan province, Iran. The research spanned the years 2021 and 2022. Average annual rainfall, maximum and minimum temperature are 350 mm, 23 and 6.6°C, respectively. Some of the monthly climatological data during both crop seasons for the studied zone was presented in Table 1.

Table 1
The monthly rainfall and average maximum and minimum temperature during the growing season in 2021 and 2022.

Months	Year	Monthly rainfall (mm)	Temperature (°C)	
			Minimum	Maximum
July	2021	0	12.3	34.7
	2022	0	11.26	34.2
August	2021	7.6	11.3	35.5
	2022	0	11.2	33.7
September	2021	0	6.8	29.1
	2022	0	7.9	29.7
October	2021	21.2	1.7	21.1
	2022	5.6	3.6	23.5

Soil condition

To assess the physical and chemical properties of the soil prior to tillage, soil samples were collected at depths of 0–30 cm and 30–60 cm. Several physical and chemical properties of the soil were determined (refer to Table 2). The content of absorbable phosphorus in the soil was extracted using the method established by Murphy and Riley (1962), while absorbable potassium was extracted using ammonium acetate, following the procedure outlined by Westerman (1991). The concentrations of phosphorus and potassium in the soil were measured using a spectrophotometer (model: Ultraviolet C 292) and a flame photometer (model: JENWAY), respectively. Furthermore, the assessment of absorbable iron by both the soil and modifiers was carried out using the DTPA method, as prescribed by (Lindsay and Norvell 1978).

Table 2
Soil and vermicompost characteristics used in the experiment

Specifications	unit	Soil depth		vermicompost
		(0–30 cm)	(0–60 cm)	
Texture	-	clay loam	clay	-
Sand	%	42.84	37.55	-
clay	%	41.28	32.24	-
sand	%	15.88	40.21	-
Field capacity	%	35	34	-
Electrical conductivity	ds m ⁻¹	0.49	0.52	1.12
pH	-	7.62	7.83	7.95
Nitrogen	%	0.08	0.05	0.9
Available potassium	mg kg ⁻¹	320	309	1.52
Available iron	mg kg ⁻¹	2.2	2.4	0.55
Available Phosphorus	%	13.5	15.5	76
Organic carbon	%	0.76	0.74	16.69
lime	%	0.89	1.16	-

Experimental design

This research was conducted using a split-plot based on a randomized complete block design (RCBD) with three replications over two consecutive years. The primary factor consisted of four irrigation levels (I1, I2, I3, and I4), representing 50%, 75%, 100%, and 125% of the quinoa crop's water requirement, respectively. The sub-factor consisted of four levels of vermicompost fertilizer (F1, F2, F3, and F4), corresponding to 0, 5, 10, and 15 tons per hectare (t ha⁻¹), respectively. It is important to note that no chemical fertilizers were used in this experiment, relying solely on vermicompost. The sub-plots within the experimental design were set at dimensions of 4 meters in length and 3 meters in width. The quinoa variety used in this study was Titicaca, chosen for its suitability for cultivation in mountainous regions. The experimental site underwent initial plowing using a moldboard plow, reaching a depth of 30 cm. Before sowing the quinoa seeds, a disc implement was employed to break up soil clods and achieve uniform ground leveling. After the plowing phase and the establishment of the experimental plot layout, vermicompost quantities allocated to each plot were carefully measured and blended with the field soil to a depth of 20 cm using a manual tiller. Each sub-plot consisted of six rows spaced 50 cm apart. Quinoa seeds were manually sown on the first of July in both years.

Characteristics of the irrigation system

An irrigation system utilizing drip-tape technology was selected for the project. The system maintained a consistent seven-day irrigation interval, with drip tapes spaced at 50 cm intervals within each plot. A volumetric meter was installed on the main pipe to monitor the amount of irrigation water, and shut-off valves were strategically placed at the start of the irrigation laterals to regulate the volume of water entering each plot. The respective diameters of the main pipe, water supply, and drip tapes were 56 mm, 32 mm, and 15 mm. To determine the depth of irrigation water, the soil moisture balance method outlined by (Xu et al. 2016) was utilized. In the first year, prior to each irrigation event, soil water content within the root zone was measured in the control plot (representing irrigation at 100% of the water requirement with zero tons of vermicompost) through daily measurements using a weighing method. Subsequently, the depth of irrigation water was calculated using Eq. (1) as per (Xu et al. 2016). In the second year, automated soil moisture monitoring was implemented by placing 12 soil moisture meter sensors at depths of 10, 20, 30, 40, 50, and 60 cm from the soil surface within the control plot. Additionally, soil moisture content at field capacity was measured in the field by creating a one-square-meter plot, following the methodology established by Daillo et al. (2013).

$$I_g = (\theta_{fc} - \theta_i) \times D_r / \eta$$

1

Where I_g is the gross irrigation depth in mm, θ_{fc} is the soil moisture content at the limit of field capacity in %, θ_i is the soil water content before irrigation in %, D_r is root zone depth in mm and η is the irrigation efficiency of drip – tape system, equal to to 90%.

Measurement

Seed protein content

The protein content of quinoa seeds was determined using the Kjeldahl method following the procedure outlined by (Nelson and Sommers 1973). Ground seeds (0.5 grams), catalyst (1.3 grams), and pure sulfuric acid (12.5 milliliters) were combined in Kjeldahl tubes. The mixture was then heated at 150 to 250 degrees Celsius for 30 minutes, followed by digestion at a temperature of 300 to 350 degrees Celsius for 1.5 hours. Subsequently, the samples underwent distillation for seven minutes in Kjeldahl with the addition of 0.1 normal hydrochloric acid. The protein percentage was calculated using Eq. 2.

$$(P\%) = [0.14 \times V_{HCL} \times K] / W \quad (2)$$

(P%): percentage of protein, V_{HCL} : Hydrochloric acid value, K: nitrogen to protein conversion factor (6.25), W: sample amount (g).

Seed phosphorus content

To determine the phosphorus content in quinoa seeds, one gram of ground and sieved seeds was placed in an oven at 550 degrees Celsius for 24 hours. After dry digestion (burning with HCl), the volume was increased to 100 ml by adding distilled water. Subsequently, 5 ml of each sample was mixed with 5 ml of a yellow solution (ammonium heptamolybdate + ammonium vanadate), and the volume was then increased to 25 ml with distilled water. After half an hour, the samples were filtered, and the resulting extract was measured using a spectrophotometer (model: Ultraviolet C 292) at a wavelength of 470 nm (Tenninghoff and Houba 2004).

Sodium, potassium and calcium

In this study, to measure the sodium and potassium contents following the method of (Chapman and Pratt 1961), quinoa seed samples were ground using a mill. Subsequently, 5 grams were placed in a porcelain pot and heated in an oven at 110 degrees Celsius for 1 hour. Then, 50 ml of 2 normal hydrochloric acids was added to each sample, and after being placed in a water bath for 20 minutes, they were filtered with filter paper and brought to a volume of 500 ml with distilled water. The samples were then analyzed using a flame photometer (model: Jenway).

Micronutrient elements (zinc, iron, copper and manganese)

To determine the levels of micronutrient elements (zinc, iron, copper, and manganese) in the quinoa seeds, the following procedure was followed. After harvesting, the samples were dried in an oven at 70 degrees Celsius for 72 hours. Once dried, the samples were ground into a fine powder. Then, 0.5 grams of the powdered plant material were weighed and placed in a porcelain mug. The mugs were then heated in a furnace at 550 degrees Celsius for 4 hours to burn off any organic matter. Next, 2.5 ml of hydrochloric acid was added to the contents of the flask, and the volume was increased to 50 cc with distilled water. The samples were then extracted, and the resulting solution was analyzed using an atomic absorption device (model AA-6300). The amount of micronutrient elements present in the samples was calculated using Eq. 3, as described by (Karla 1998).

$$(3)X = \frac{a \times v \times b \times 100}{m \times Dm}$$

X = concentration of micro elements (mg kg^{-1}), a = number read from the device (mg kg^{-1}), b = dilution factor (mg kg^{-1}), m = weight of plant matter (g), Dm = % of dry matter.

Percentage of seed oil

To determine the percentage of oil, the seed samples were first powdered using an electric mill. Then, the continuous Soxhlet extractor method was used with 300 cc of n-hexane solvent for 6 hours, following the (AOAC 2005) guidelines.

Data analysis

Subsequent data analysis was conducted using SAS version 9.1. To compare treatment means, the LSD (Least Significant Difference) test was employed. Additionally, graphical representations of the data were

Results and Discussion

Seed Yield

Statistical analysis showed significant effects of irrigation and vermicompost levels on quinoa seed yield ($p < 0.001$). However, the interaction between irrigation and vermicompost was not statistically significant ($p < 0.01$ and $p < 0.05$). The highest seed yield of $2131.51 \text{ kg ha}^{-1}$ was achieved with 125% of water requirement irrigation, while the maximum yield of $1884.01 \text{ kg ha}^{-1}$ was recorded with 15 t ha^{-1} of vermicompost application. Vermicompost utilization significantly enhanced seed yield across all irrigation levels (Table 3).

Biological Yield

Analysis of variance (ANOVA) indicated significant effects of irrigation and vermicompost on quinoa biological yield ($P < 0.01$). Notably, the interactions of irrigation $\times$ vermicompost and year $\times$ irrigation $\times$ vermicompost were not statistically significant. Application of vermicompost increased biological yield compared to non-application, with no significant differences observed among vermicompost levels. Biological yield ranged from $3457.21 \text{ kg ha}^{-1}$ in the control group to $4100.25 \text{ kg ha}^{-1}$ with 15 t ha^{-1} of vermicompost (Table 3).

phosphorus, potassium and calcium Concentration

Both irrigation and vermicompost levels had a significant impact on the concentrations of phosphorus, potassium, and calcium in the seeds, although their interaction was not statistically significant ($P < 0.01$). Phosphorus, potassium, and calcium concentrations in the seeds were higher at 50% and 75% of the water requirement for irrigation compared to full (100%) and 125% irrigation levels. Furthermore, seed phosphorus, potassium, and calcium concentrations increased with vermicompost application. In our study, mean comparison of different levels of vermicompost on the phosphorus concentration of quinoa seeds revealed a significant increase in seed phosphorus concentration with vermicompost application compared to the control treatment (no application of vermicompost). The values for this trait were statistically similar with an increase in vermicompost level from 5 to 10 tons per hectare, at 0.29 and 0.33 mg g^{-1} , respectively. The lowest (0.22 mg g^{-1}) and highest (0.36 mg g^{-1}) seed phosphorus concentrations were observed in the treatments with no application of vermicompost and $15 \text{ tons per hectare}$ of vermicompost, respectively. Mean comparison of effects of different irrigation levels on seed potassium concentration showed that an increase in irrigation level led to a significant increase in the potassium concentration of quinoa seeds. However, the amount of this trait decreased in the treatment with 120% of the water requirement compared to the treatment with 100% of the water requirement, at 3.68 and 4.43 mg g^{-1} , respectively. The lowest amount of seed potassium was recorded in the treatment with 50% of the water requirement, at 2.08 mg g^{-1} . Mean comparison of the effects of vermicompost levels on the potassium concentration of seeds showed that the application of this fertilizer led to a

significant increase in this element compared to the treatment without fertilizer. Concurrently with the increase in vermicompost, the amount of calcium in seeds also increased. The highest (2.71 mg g^{-1}) and lowest (2.09 mg g^{-1}) seed calcium concentrations were observed in the treatments with the application of 15 tons per hectare of vermicompost and no application of vermicompost, respectively (Table 3).

Table 3. Means comparison of irrigation and vermicompost effects on the seed yield, biological yield and Concentrations phosphorus, potassium and calcium in Seed of quinoa in two years of experiment.

Treat	Seed yield	Biological yield	P concentration	K concentration	Ca concentration
	(kg ha ⁻¹)			(mg kg ⁻¹)	
	Irrigation level				
50 %	1065.91 ^d	2678 ^d	0.24 ^c	2.08 ^d	2.78 ^a
75 %	1284.15 ^c	3360.1 ^c	0.28 ^{bc}	3.09 ^c	2.63 ^b
100 %	1987.17 ^b	4525.2 ^b	0.31 ^b	4.43 ^a	2.34 ^c
125 %	2131.51 ^a	5075.1 ^a	0.37 ^a	3.68 ^b	2.04 ^d
	Vermicompost level				
0 ton	1441.53 ^b	3457.21 ^b	0.22 ^c	2.62 ^d	2.09 ^d
5 ton	1540.37 ^b	4034.81 ^a	0.29 ^b	3.05 ^c	2.41 ^c
10 ton	1702.83 ^a	4100.25 ^a	0.33 ^b	3.64 ^b	2.52 ^b
15 ton	1784.01 ^a	4046.64 ^a	0.36 ^a	3.97 ^a	2.78 ^a
The same letters indicate statistically insignificant differences (P<0.05).					

Nitrogen concentration

Nitrogen concentration in quinoa seeds was significantly influenced by the year, irrigation levels, and vermicompost application, including their triple interaction ($P < 0.01$). Notably, there was an increase in seed nitrogen concentration in the second year, with varying effects of irrigation and vermicompost levels. Upon examining the interaction effect of year with different irrigation and vermicompost levels, it was observed that as the vermicompost level increased across all irrigation treatments, the nitrogen percentage in quinoa seeds also increased. Additionally, seed nitrogen concentration was higher in low irrigation treatments compared to full irrigation and 125% of the water requirement (Fig. 1).

Sodium concentration

The results highlighted that sodium concentration was significantly affected by irrigation $\times$ vermicompost application ($P < 0.001$). also, the interaction effect of vermicompost $\times$ year was statistically significant ($p < 0.001$). Seed sodium content ranged from 0.82 mg kg^{-1} in the 125% irrigation and without vermicompost to 1.52 mg kg^{-1} in the treatment 50% irrigation and 15 tons per hectare vermicompost. Mean comparison of interaction of different levels of irrigation and vermicompost on sodium content of quinoa seeds showed that the increase of irrigation levels decreased the values of this trait. Increasing the levels of vermicompost application in low-irrigation treatments increased the amount of sodium in the seeds. However, the application of different levels of vermicompost in the treatment of 100% plant water requirement did not create a statistically significant difference in the values of this trait (Fig. 2, 3).

Zinc concentration

The study revealed that zinc concentration in quinoa seeds was significantly influenced by year, irrigation, and vermicompost, as well as their triple interaction ($p < 0.01$). Although the sodium concentration of quinoa seeds remained consistent across the two years of the experiment, the effects of irrigation and vermicompost levels varied. Upon analyzing the interaction between different levels of irrigation and vermicompost, as well as year, on the zinc content of quinoa seeds, it was observed that the trend of changes in zinc concentration in seeds was consistent in both years. The highest zinc concentration in the seeds was recorded in the treatment with 15 tons per hectare of vermicompost and 125% of the plant's water requirement, with values of 20.22 mg g^{-1} in the first year and 21.83 mg g^{-1} in the second year (Fig. 4).

Fe concentration

The Fe concentration of quinoa seeds was significantly affected by both irrigation and vermicompost treatments during the 2021 and 2022 growth periods ($p < 0.001$). Notably, the triple interaction effect of year $\times$ irrigation $\times$ vermicompost was not statistically significant (Table 4).

Mn concentration

The addition of varying proportions of vermicompost to the soil where quinoa was grown resulted in an increase in Mn concentration. The triple interaction effect of year $\times$ irrigation $\times$ vermicompost was not statistically significant. Mn concentration in water-stress treatments exceeded that in treatments with adequate water for the crop. The highest Mn seed concentration (63.39 mg g^{-1}) was observed in the treatment with 15 tons per hectare of vermicompost and an irrigation level of 50% of the plant's water requirement (Table 4).

Cu concentration

The triple interaction effect of year $\times$ irrigation $\times$ vermicompost was found to be not statistically significant. The Cu concentration in quinoa seeds showed sensitivity to the interaction between varying levels of irrigation and vermicompost application. Specifically, an increase in soil water content was associated with higher Cu concentration, while higher levels of vermicompost led to an increase in Cu concentration content (Table 4).

Seed oil

The study revealed a significant impact of irrigation $\times$ vermicompost application on seed oil content ($p < 0.001$). However, the triple interaction of year $\times$ irrigation $\times$ vermicompost was not statistically significant ($p < 0.001$ and $p < 0.05$). The seed oil content ranged from 2.31% under 50% irrigation stress without vermicompost to 4.2% under 125% irrigation level with 15 tons per hectare of vermicompost. The comparison of means indicated a substantial increase in oil percentage with the use of vermicompost across all tested irrigation levels. Conversely, in treatments without vermicompost, irrigation did not lead to an increase in the oil percentage. The oil percentage in the irrigation treatments at 50% of the plant's water requirement with 10 and 15 tons per hectare of vermicompost was statistically similar at 3.37%

and 3.52%, respectively, to the oil percentage in the treatment at 75% of the plant's water requirement with 5 tons per hectare of vermicompost, which was 3.93% (Table 4).

Table 4. Mean comparison of the effect of different levels of irrigation and vermicompost on Fe, Mn and Cu concentration and seed oil.					
Irrigation (%)	Vermicompost (t ha ⁻¹)	Fe concentration	Mn concentration	Cu concentration	Seed oil
		mg kg ⁻¹			%
50	0	228.04 ^j	49.54 ^c	1.91 ^d	2.31 ^d
	5	236.34 ^j	53.45 ^{bc}	2.23 ^c	3 ^{bc}
	10	244.01 ⁱ	59.42 ^b	2.25 ^c	3.52 ^b
	15	262.66 ^h	63.39 ^a	2.62 ^{bc}	3.37 ^b
75	0	245.67 ⁱ	43.35 ^d	2.29 ^c	2.79 ^c
	5	272.16 ^g	48.29 ^c	2.26 ^c	3.59 ^b
	10	290.81 ^f	56.25 ^b	2.22 ^c	3.8 ^{ab}
	15	302.26 ^e	47.54 ^b	2.25 ^c	4.2 ^a
100	0	275.01 ^g	41.06 ^d	3.12 ^b	2.8 ^c
	5	306.48 ^d	42.4 ^d	3.29 ^{ab}	4 ^a
	10	352.06 ^c	43.34 ^d	3.25 ^{ab}	3.9 ^a
	15	368.75 ^a	53.32 ^{bc}	3.82 ^a	4 ^a
125	0	275.06 ^g	4.32 ^d	3 ^b	2.9 ^c
	5	309.03 ^d	49.94 ^d	2.77 ^c	3.9 ^a
	10	346.74 ^c	55.4 ^b	3.26 ^{ab}	4.1 ^a
	15	370.07 ^a	54.64 ^b	3.23 ^{ab}	3.8 ^a
The same letters indicate statistically insignificant differences (P < 0.05).					

The findings of numerous studies have demonstrated that water deficiency during seed filling reduces seed yield per unit area by impeding photosynthesis. Water stress during the seed filling stage, particularly when coupled with elevated temperatures, accelerates leaf aging, shortens the seed filling period, decreases average seed weight, and reduces overall yield. This is attributed to the diminished

transfer of photosynthetic materials to developing seeds (Piri et al. 2022). The higher seed yield in stress-free conditions can be attributed to the availability of ample water for the plant, which enhances yield components and ultimately boosts seed yield. Sufficient water during plant growth enhances source and sink strength, leading to increased seed yield (Piri et al. 2022).

In addition to its nutrient richness compared to other fertilizers, vermicompost possesses characteristics such as gradual nutrient release, particularly nitrogen, which mitigates nitrate leaching. Calcium and potassium compounds in vermicompost reduce soil acidity and increase soil organic matter, thereby enhancing water and nutrient retention in the soil (Wang et al. 2022). Conversely, augmenting seed yield through increased vermicompost application can be achieved by promoting plant vegetative growth, enhancing reserve material production, improving flower fertility, and increasing thousand-seed weight, ultimately leading to increased seed yield (Arancon et al. 2022). Our results corroborate the earlier findings of (Ranva and Singh 2021; Wang et al. 2022). It appears that in the current experiment, the reduced biological yield in treatments receiving less water than the plant's requirement is due to water stress leading to reduced stem and leaf formation, consequently diminishing the plant's dry matter yield. In simpler terms, as drought stress increases, soil moisture decreases during plant growth, leading to reduced material transfer and limiting the production of photosynthetic materials in plants. The decrease in plant photosynthesis due to stress factors also reduces hydrostatic pressure and material transfer rate, which may explain the decreased biological performance in treatments with low irrigation (González-Teuber et al. 2018).

The presence of vermicompost in the soil enhances soil fertility, storage capacity, and porosity. These compounds gradually release nutrients, making them available to plants over time. Vermicompost fertilizers not only provide essential nutrients for plant growth but also increase water availability, promote vegetative growth, and enhance biomass production (Singer et al. 2007). Vermicompost contains vital elements like nitrogen, phosphorus, potassium, calcium, iron, manganese, copper, zinc, and boron in forms that are readily usable by plants and soluble in water (Wang et al. 2022). These findings align with previous studies (Rani et al. 2020; Demir 2019).

The concentration of nutrients in seeds increases with higher irrigation levels due to improved soil moisture, nutrient availability, and enhanced nutrient absorption by plants. Continuous soil moisture availability under drip irrigation helps dissolve nutrients near the roots, facilitating better absorption at higher irrigation levels (Tang et al. 2023). Nutrient absorption is hindered in water scarcity due to reduced transpiration, disruptions in transport systems, membrane permeability, and decreased root absorption capacity. Lower soil moisture reduces nutrient diffusion to the roots and impairs root system efficiency. Phosphorus fixation in dry conditions contributes to its scarcity in plants (Bardel et al. 2023). Studies have shown reduced phosphorus levels in quinoa seeds under stress compared to control treatments (EL-Tahan et al. 2019).

It seems that vermicompost, rich in nutrients and microorganism activity, facilitates plant access to essential resources like phosphorus by stimulating soil microorganisms and aiding nutrient absorption.

Additionally, the compounds in vermicompost acidify the rhizosphere environment, leading to the release of insoluble phosphorus as H^+ ions are replaced with calcium ions. Phosphorus, being immobile in soil, is absorbed by roots when they encounter organic or inorganic substances containing its absorbable form (Hanč et al. 2018). Research indicates that potassium concentrations decrease under drought stress due to reduced potassium availability in dry conditions. Higher irrigation levels, by increasing soil moisture content, result in a greater proportion of monovalent ions like potassium in the soil solution compared to divalent ions such as magnesium and calcium. Consequently, plants absorb a higher percentage of potassium at these levels and store it in their seeds. As soil moisture decreases, clay colloids gradually bind potassium more tightly to their surfaces, inhibiting the release of these ions. Furthermore, under water stress, plant growth, including root absorption activity, is hindered, reducing the plant's ability to take up potassium from the clay colloids, resulting in decreased absorption of these elements (Rani et al. 2020). Conversely, the decline in potassium concentration in seeds during drought stress may be attributed to the translocation of these elements from the seed to the root, where potassium serves as an osmotic regulator in such conditions. Potassium ions play a crucial role as a secondary messenger in plants, participating in the transmission of diverse signals, making it a key component in plants' response to drought (Osuagwu et al. 2010). The increase in potassium concentration observed with vermicompost application can be linked to enhanced nutrient cycling and improved physical and biological soil properties. Additionally, vermicompost boosts the population of beneficial soil microorganisms, which in turn secrete organic acids, creating an acidic rhizosphere environment that enhances plant access to potassium (Agegnehu et al. 2016).

The decrease in calcium content in the complete irrigation treatments can be attributed to several factors (Bardel et al. 2023). Firstly, the large water limitations imposed in those treatments may have led to reduced oxygen supply to the roots. This, in turn, can hinder respiration, nutrient absorption, and other root activities, ultimately affecting calcium uptake. In a separate study investigating the impact of different irrigation levels on quinoa seeds, it was found that the concentration of calcium was higher in the low irrigation treatment compared to the full irrigation treatment (Walters et al. 2016). This suggests that reduced water availability may have a positive effect on calcium accumulation in the seeds.

The increase in seed nitrogen concentration with a decrease in soil moisture can be attributed to a concentration effect. When soil moisture decreases, the growth rate of the plant's aerial parts tends to decrease more than the rate of nitrogen absorption (Bardel et al. 2023). As a result, the nitrogen becomes more concentrated in the seeds. In treatments that received more water, one of the main reasons for the decrease in seed nitrogen concentration is related to nitrogen wastage, particularly through leaching or washing away of nitrogen from the soil (Rani et al. 2020). This suggests that excessive watering can lead to the loss of nitrogen, thereby reducing its concentration in the seeds.

In agriculture, when there is sufficient water available in the field during the growth period, plants do not experience water shortage during the physiological ripening stage. Irrigation improves the plant's condition by enhancing photosynthesis and enabling nitrogen absorption to continue throughout the growth period (Bole and Dubetz 1986). Organic fertilizers, such as vermicompost, contain high levels of

organic compounds and serve as rich sources of nutrients, particularly nitrogen. Incorporating vermicompost into the soil not only increases the supply of essential nutrients for plants but also enhances soil physical conditions and vital processes. This creates an optimal substrate for root growth, promotes aerial organ development, and boosts nitrogen absorption (Arancón et al. 2022).

In stressful conditions, the accumulation of sodium in various plant tissues, especially seeds, is a result of increased root absorption and xylem-to-leaf transport. This mechanism establishes osmotic balance in the plant, facilitating enhanced water uptake (EL-Tahan et al. 2019).

Vermicompost is a rich source of nutrients, particularly nitrogen, that can enhance plant growth and performance. Studies have shown that the use of vermicompost fertilizer can increase the absorption and transfer of sodium to plant seeds, which helps establish osmotic balance and facilitates water uptake (Gutierrez-Miceli et al. 2007). However, the absorption of zinc is primarily through active absorption mechanisms, and drought stress can limit the transfer of this element to the seed, resulting in decreased zinc concentration. Additionally, drought stress can reduce the amount of active absorption of elements and the production of photosynthetic substances, leading to decreased absorption of elements and reduced growth (Marschner 2012; Osborne et al. 2022).

The high percentage of humic substances in vermicompost, with their low molecular weight, plays a crucial role in stabilizing cell membranes and enhancing the absorption of various essential nutrients, including zinc (Li et al. 2017). Furthermore, the decomposition of organic fertilizers, particularly vermicompost, leads to a decrease in soil pH and the formation of zinc chelates through the addition of organic compounds, effectively increasing the availability of zinc. The presence of short-chain organic matter in the soil enhances the mobility and solubility of zinc, making it more readily available to plants through bonding with zinc (Marschner 2012).

Low soil moisture levels have been found to reduce the absorption of iron by plant roots, which justifies the decrease in iron concentration in drought stress treatments (EL-Tahan et al. 2019). The characteristics of soil organic matter play a role in the availability of low-use nutrients in the soil. As organic matter decomposes, the nutrients it contains are released. This decomposition process also leads to a decrease in soil pH, resulting in increased concentrations of nutrients, particularly low-use elements like iron, in the soil. Research has shown that the addition of vermicompost to the soil can enhance the solubility of iron by forming a complex with it, thereby preventing its precipitation (Li et al. 2017). Other studies have reported a significant decrease in the concentration of iron in quinoa seeds under drought stress (Aly et al. 2018; EL-Tahan et al. 2019).

An increase in manganese concentration in seeds under drought stress may be attributed to the reduction in biomass caused by water scarcity, leading to a higher accumulation of this element in seeds. Our study suggests that under well-irrigated conditions, an increase in iron absorption could potentially lead to a decrease in manganese concentration and uptake by plants due to their antagonistic relationship (Yanga et al. 2015). Drought conditions can limit root access to cations, resulting in reduced copper concentration in seeds. Furthermore, decreased soil moisture levels can restrict plant access to

low-demand nutrients such as iron, zinc, copper, and manganese. Consequently, increased drought stress can reduce copper absorption, leading to lower concentrations in leaves and seeds (Arndt et al. 2021). Additionally, research findings indicate that the use of vermicompost not only enhances soil's absorbable copper levels but also improves soil fertility and plant nutrition by promoting nutrient cycling (Li et al. 2017).

The oil percentage in seeds is a quantitative trait controlled by multiple genes, and the decrease in oil percentage under drought stress can be attributed to the damage of numerous genes regulating seed oil content (Sincik et al. 2013). The findings of our study align with previous research in this area, indicating that water stress leads to a reduction in oil percentage due to the impact of stress on the seed's ability to accumulate oil. Drought stress negatively affects seed oil percentage by hampering the seed's capacity to absorb assimilates and convert them into oil (Petcu and Stanciu 2021). Adequate water availability during plant growth appears to promote an increase in seed weight and oil storage. Conversely, the decrease in seed oil content under drought stress may result from a shortened seed filling period and reduced seed weight. Furthermore, the limited availability of carbohydrates for oil synthesis due to drought stress contributes to the decrease in oil percentage (Si et al. 2003).

The oil percentage in seeds is a heritable trait influenced by genetic factors, with the production of oil being derived from compounds generated during photosynthesis. Enhancing plant growth conditions can potentially elevate the oil percentage in seeds (Singer et al. 2007). Utilizing vermicompost fertilizer can create more favorable conditions for root and organ growth, leading to improved water and nutrient uptake. Additionally, vermicompost can help balance soil acidity and enhance nutrient absorption, ultimately resulting in an increase in seed oil percentage (Wang et al. 2022).

Conclusions

In conclusion, the findings of this study demonstrate that the application of vermicompost under varying irrigation levels positively impacted the yield and components of quinoa, particularly under low irrigation conditions. Vermicompost proved to mitigate the effects of water stress treatments, especially in comparison to moderate (75% of water requirements) and severe (50% of water requirement) irrigation levels, which significantly decreased both biological and seed yield. The analysis of experimental data revealed that different levels of vermicompost effectively moderated the impact of water stress under low irrigation treatments by enhancing water and nutrient absorption, improving soil conditions, and sustaining quinoa functionality while maximizing water resources. Furthermore, as organic fertilizers, vermicompost addresses the limitations associated with chemical fertilizers, such as insolubility under deficient conditions and inadequate absorption by plants.

By increasing irrigation and incorporating vermicompost fertilizer into the soil, a gradual increase in nitrogen, phosphorus, potassium, iron, zinc, and copper was observed. The highest average levels of nitrogen, phosphorus, iron, potassium, and zinc were found in the treatment with 125% of the water requirement and 15 tons per hectare of vermicompost. However, the highest copper concentration was

observed in the full irrigation treatment with 15 tons of vermicompost per hectare. Increasing irrigation levels led to a reduction in seed potassium concentration, with the lowest concentration observed in the treatment receiving 125% of the water requirement. The substrates containing vermicompost have a high nutrient content, and the gradual release of these elements results in more efficient plant nutrition, leading to increased seed concentration. Furthermore, the use of vermicompost in drought stress conditions modifies the physical and chemical properties of the soil and enhances soil moisture retention, ultimately increasing the concentration of quinoa seed elements compared to treatments without vermicompost. Given the deficiency of organic matter in most Iranian soils, it is recommended to use organic fertilizers such as vermicompost to improve seed nutrient concentration and enhance the physical and chemical properties of the soil.

Declarations

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to affect the work reported in this paper.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data Availability Statement

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Author Contribution

Diba Sheykhi Sanandaji, Gholamreza Heidari and Parviz Fathi wrote the main manuscript text and prepared the figures and Habib Khodaverdiloo and Zahed Sharifi reviewed the manuscript

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Figures

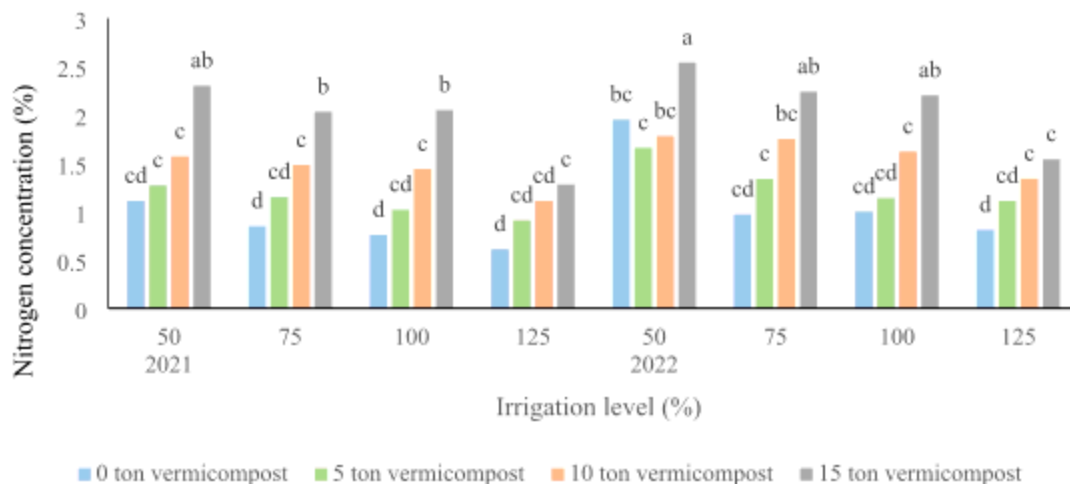


Figure 1

Mean comparison of effect of different year × different irrigation levels (50, 75, 100 and 125% of water requirement) × vermicompost fertilizer (0, 5, 10 and 15 tons per hectare) on seed nitrogen concentration. The same letters indicate statistically insignificant differences ($P < 0.05$).

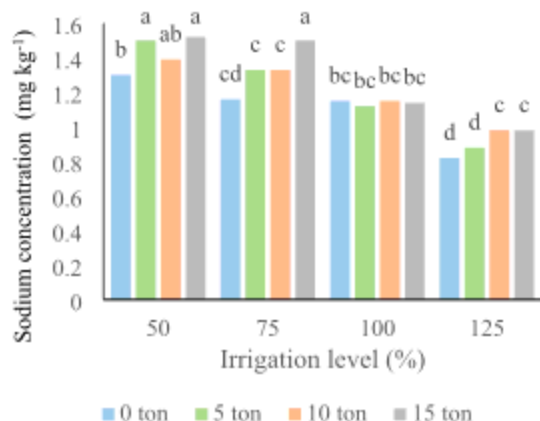


Figure 2

The effect of different levels of irrigation (50, 75, 100, and 125% of the plant's water requirement) and vermicompost (0, 5, 10, and 15 tons per hectare) on seed sodium concentration in two years of experiment. The same letters indicate statistically insignificant differences ($P < 0.05$).

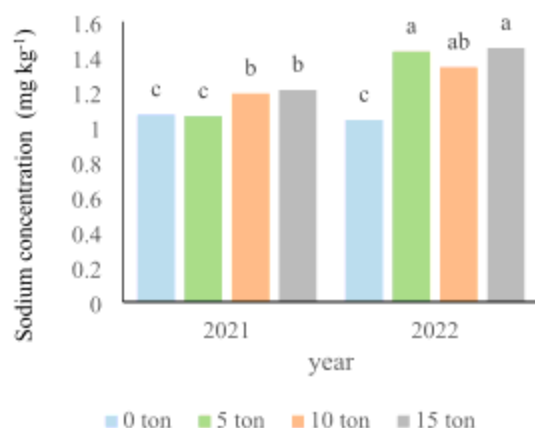


Figure 3

The effect of different levels of year and vermicompost (0, 5, 10, and 15 tons per hectare) on seed sodium concentration in two years of experiment. The same letters indicate statistically insignificant differences ($P < 0.05$).

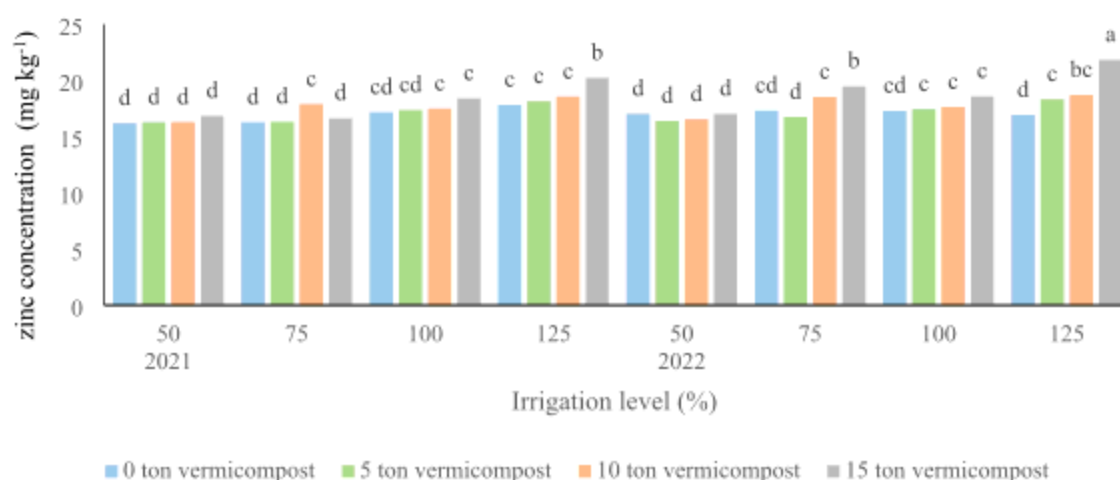


Figure 4

Mean comparison of the effect of different year $\times$ different irrigation levels (50, 75, 100 and 125% of water requirement) $\times$ vermicompost fertilizer (0, 5, 10 and 15 tons per hectare) on zinc concentration. The same letters indicate statistically insignificant differences ($P < 0.05$).