

Response of Two Quinoa (*Chenopodium quinoa* Willd.) Cultivars to Different Plant Densities in Terms of Growth and Productivity

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Abstract

This study aimed to evaluate the performance of two quinoa (*Chenopodium quinoa* Willd.) cultivars, Giza-1 and Red Carina, under three within-row plant spacings (10, 15, and 20 cm) during the 2024/2025 and 2025/2026 growing seasons at Abu Jarash Farm, Faculty of Agriculture, Damascus University, Syria. The experiment was conducted using a split-plot design with three replicates. The evaluated traits included plant height, panicle length, stem diameter, grain weight per plant, grain yield, biological yield, and harvest index.

The results revealed that Red Carina significantly outperformed Giza-1 in plant height, stem diameter, grain weight per plant, grain yield, and harvest index, whereas no significant differences were observed between the two cultivars in panicle length or biological yield. The 20-cm plant spacing produced the highest mean grain yield (2.172 t ha⁻¹), biological yield (13.78 t ha⁻¹), and grain weight per plant (31.93 g). The Red Carina treatment at 20-cm spacing achieved the highest grain yield (2.837 t ha⁻¹) and biological yield (17.38 t ha⁻¹), whereas the highest harvest index (29.48%) was recorded for Red Carina planted at 10-cm spacing.

These findings highlight the importance of selecting suitable cultivars and plant spacing to improve quinoa productivity. Under the conditions of this study, Red Carina planted at 20-cm spacing appears to be the most promising treatment for grain production. Further trials across different growing seasons and locations, together with an assessment of economic feasibility, are recommended before formulating a general agronomic recommendation.

Key words: Quinoa; *Chenopodium quinoa* Willd.; cultivars; plant spacing; grain yield; biological yield; harvest index.

1-Introduction:

Quinoa (*Chenopodium quinoa* Willd.) is a promising grain crop that has attracted increasing global attention because of its high nutritional value and its ability to adapt relatively well to a wide range of environmental conditions. Quinoa belongs to the family Amaranthaceae and originated in the Andean region of South America, where it has been traditionally cultivated for thousands of years before its cultivation expanded to various regions worldwide. Growing interest in food security and crop diversification has further strengthened its position as a crop capable of contributing to the sustainability of agricultural systems, particularly in areas facing challenges associated with water scarcity or limited agricultural resources (Bazile et al., 2016; Hinojosa et al., 2018).

The nutritional importance of quinoa stems from its grain composition, which includes proteins, lipids, minerals, and a range of important nutritional compounds. In addition, its vegetative parts can be utilized for certain food and feed purposes. Quinoa cultivars also differ in their morphological, phenological, and yield-related traits, as well as in their ability to adapt to different environmental conditions. Therefore, selecting an appropriate cultivar and determining suitable agronomic practices are essential factors for improving field performance and crop productivity (Hinojosa et al., 2018; Angeli et al., 2020).

Plant density is an important agronomic factor affecting plant growth and development, canopy formation, and final crop yield. Together with plant distribution within a unit area, plant density determines the intensity of competition among plants for light, water, nutrients, and available growing space. Increasing plant density may improve the utilization of cultivated land and increase the number of productive plants per unit area. However, exceeding the optimum density may intensify competition among plants, reduce certain individual plant traits, such as stem diameter, or increase susceptibility to lodging under some conditions. Consequently, higher productivity is not necessarily associated with a continuous increase in plant density; rather, crop responses depend on the balance between the number of plants per unit area and their capacity for growth and grain formation (Al-Jbawi et al., 2022; Asher et al., 2022).

Investigating plant density in quinoa is particularly important because its cultivars exhibit considerable variation in their responses to plant arrangement and environmental conditions. A study conducted in central Syria reported significant differences among the investigated cultivars and plant densities, as well as a significant interaction between these factors for the traits examined. Furthermore, the density associated with the best performance of certain traits varied according to the cultivar and the trait under consideration. These findings emphasize the need to evaluate plant density in relation to cultivar genetic background and prevailing agronomic conditions rather than adopting a single density for all cultivars (Al-Jbawi et al., 2022).

Similarly, Asher et al. (2022), in a study investigating the effects of inter-row spacing on quinoa growth, yield, and grain quality under Mediterranean climatic conditions, reported that narrower row spacing was associated with increases in several yield-related indicators, whereas wider spacing was associated with greater stem diameter. However, not all traits exhibited the same response, highlighting

the importance of balancing productivity with morphological characteristics and grain quality when determining an appropriate planting system.

Despite the increasing number of studies investigating plant density in quinoa, determining the optimum density remains dependent on the cultivar, growing environment, planting system, and target traits. Therefore, local studies comparing the responses of different cultivars to varying plant densities are important for generating scientific evidence to improve crop management and enhance the efficiency of land use.

Accordingly, the present study aimed to evaluate the responses of two quinoa cultivars, Giza-1 and Red Carina, to different plant densities by investigating their effects on growth and yield-related traits. The study also sought to identify differences between the two cultivars in their responses to the evaluated density levels and to determine the most suitable treatment under the environmental and agronomic conditions in which the experiment was conducted.

2. Materials and Methods

2.1. Experimental Site and Plant Materials

Two quinoa (*Chenopodium quinoa* Willd.) cultivars, Giza-1 and Red Carina, were used in this study. Some of their morphological and yield-related characteristics are presented in Table 1, based on unpublished data from the Sugar Beet Research Department, Agricultural Scientific Research.

The experiment was conducted during the 2024/2025 and 2025/2026 growing seasons at Abu Jarash Farm, Faculty of Agriculture, Damascus University, Syria. Sowing was carried out in mid-February, and harvesting took place in August in each growing season.

Three plant spacing treatments were evaluated: 10 × 30 cm (S1), 15 × 30 cm (S2), and 20 × 30 cm (S3), where the first dimension represents the spacing between plants within a row and the second represents the spacing between rows. The factorial combination of the two cultivars and three plant spacing treatments resulted in six experimental treatment combinations, each evaluated in three replicates.

Table 1. Selected morphological and yield-related characteristics of the quinoa cultivars under investigation

Characteristic	Giza-1	Red Carina
Plant growth habit	Erect	Erect
Plant height (cm)	90–125	90–120
Branching intensity	Moderate to strong	Moderate to strong
Plant colour	Green	Reddish-brown to purple
Flower colour	Light yellow to cream	Pinkish-red
Grain colour	Creamy white	Creamy white
Average yield (t ha ⁻¹)	1.8–3.0	1.5–2.5

The experimental field was prepared by performing two ploughing operations using a mouldboard plough, each to a depth of 30 cm, with the second operation perpendicular to the first. A third tillage operation was subsequently performed using a cultivator to a depth of 10 cm to break up soil clods, refine the soil tilth, and level the field. The field was then laid out in rows, maintaining a constant inter-row spacing of 30 cm while varying the within-row plant spacing according to the three treatments under investigation: 10, 15, and 20 cm. Each experimental plot consisted of six rows.

Seeds were sown manually, and thinning and gap filling were carried out before the plants reached the stage of emergence of the second pair of true leaves. Manual hoeing was performed as needed throughout the growing season to control competing weeds. Specific pesticides were applied when necessary to control diseases and insect pests.

Fertilizer application rates were determined based on soil analysis and were equivalent to 120 kg N, 50 kg P₂O₅, and 50 kg K₂O ha⁻¹.

Nitrogen fertilizer was applied as urea containing 46% N in two equal doses. The first dose was applied at sowing, and the second at the flowering stage. Phosphorus fertilizer was applied before sowing as triple superphosphate containing 46% P₂O₅, whereas potassium fertilizer was applied as potassium sulfate containing 50% K₂O, in accordance with the soil analysis results.

Each experimental plot measured 4 × 2 m, giving a total area of 8 m². A distance of 1 m was maintained between replicates, and the experimental area was surrounded by a 1-m-wide border on all sides.

Plants were harvested manually from the two inner rows of each six-row experimental plot to minimize edge effects. The panicles were collected and threshed manually to extract the grains. Chaff and other impurities were separated from the grains by winnowing. The grains were dried before storage in preparation for the measurements required to determine grain yield and thousand-grain weight.

2.2. Measured Traits

2.2.1. Morphological Traits

Morphological traits were measured on ten plants randomly selected from the harvested rows. The traits included:

- **Plant height (cm):** Measured from the soil surface to the growing tip of each plant.
- **Stem diameter (cm):** Measured as the diameter of the plant stem.
- **Panicle length (cm):** Measured as the length of the main flowering inflorescence (panicle).

The mean value of each trait was calculated from the plants measured within each experimental plot.

2.2.2. Yield-Related Traits

Yield-related traits were determined using the plants and grains obtained from the designated harvest area of each experimental plot. The measured traits included:

- **Grain weight per plant (g):** The weight of grains produced by an individual plant.

- **Grain yield (t ha^{-1}):** The quantity of grain produced per unit area, converted to tonnes per hectare.
- **Thousand-grain weight (g):** The weight of a sample consisting of 1,000 grains.
- **Biological yield (t ha^{-1}):** Defined as the total dry biomass of the plants within the designated harvest area and converted to tonnes per hectare.
- **Harvest index (%):** Calculated as the ratio of grain yield to biological yield, multiplied by 100 (GonzaAlez et al., 1999).

2.3. Experimental Design and Statistical Analysis

The experiment was conducted using a split-plot design, with the two quinoa cultivars assigned to the main plots and the three plant spacing treatments assigned to the subplots. Thus, the experiment comprised six treatment combinations resulting from the interaction between cultivar and plant spacing, with three replicates in each growing season.

Data from the two growing seasons were subjected to a combined statistical analysis using GenStat software to evaluate the effects of the experimental factors and their interactions, while accounting for the effect of growing season

3. Results and Discussion

3.1. Effect of Cultivar and Plant Density on Mean Quinoa Plant Height

The results revealed significant differences in mean quinoa plant height between cultivars and plant density levels. The interaction between these two factors also indicated differences in the responses of the two cultivars to the different plant spacing treatments.

Red Carina significantly outperformed Giza-1 in plant height, with a mean of 119.6 cm compared with 99.5 cm for Giza-1, representing an increase of 20.1 cm, or approximately 20.2%. This difference may be attributed to genetic variation between the cultivars in vegetative growth habit, stem elongation, and growth allocation among plant organs. These findings highlight the importance of genetic background in determining quinoa plant height, while emphasizing that this superiority should be interpreted under the experimental conditions rather than generalized to all agricultural environments.

Mean plant height increased from 99.5 cm at a within-row spacing of 10 cm (D1) to 107.0 cm at 15 cm (D2), and subsequently to 122.2 cm at 20 cm (D3). The difference between D1 and D2 was not significant, whereas D3 significantly exceeded both treatments.

These findings indicate that wider within-row spacing, accompanied by lower plant density, was associated with increased quinoa plant height under the experimental conditions. This trend may be related to changes in competition for light and other available resources or to differences in vertical growth responses according to the space available to each plant.

The importance of managing plant spacing and density is consistent with the study by Asher et al. (2022), which investigated quinoa under Mediterranean climatic conditions and examined the effects of planting spacing on growth and yield-related traits. Their findings indicated that quinoa traits may respond differently depending on growing conditions and planting dates. Wang et al. (2020) also

investigated plant density among a range of agronomic practices affecting quinoa growth and productivity, supporting the importance of evaluating density within an integrated crop management system.

The interaction between cultivar and plant density showed that the greatest mean plant height was obtained with Red Carina at a within-row spacing of 20 cm (D3), reaching 136.7 cm and belonging to statistical group (a). In contrast, the lowest mean height was recorded for Giza-1 at 10-cm spacing (D1), reaching 94.2 cm and belonging to group (d).

For Red Carina, mean plant height increased from 104.9 cm at D1 to 136.7 cm at D3, an increase of 31.8 cm. For Giza-1, height increased from 94.2 to 107.7 cm, an increase of 13.5 cm. This suggests that Red Carina exhibited a greater increase in plant height in response to wider within-row spacing than Giza-1.

However, this descriptive comparison alone is insufficient to establish that the cultivars differed significantly in their responses to changes in spacing. Such a conclusion requires an appropriate interaction test and suitable comparisons between treatment means. Furthermore, greater plant height does not necessarily imply higher productivity. Therefore, these findings should be interpreted alongside traits such as grain weight per plant, grain yield per unit area, biological yield, and harvest index when drawing overall conclusions.

Table 2. Effects of cultivar and plant density on mean quinoa plant height (cm) during the 2024/2025 and 2025/2026 growing seasons

Cultivar	D1 (10 × 30 cm)	D2 (15 × 30 cm)	D3 (20 × 30 cm)	Cultivar mean
Giza-1	94.2 d	96.7 cd	107.7 bc	99.5 b
Red Carina	104.9 cd	117.3 b	136.7 a	119.6 a
Plant density mean	99.5 b	107.0 b	122.2 a	109.6
LSD (0.05)	Cultivar (V) = 6.63; Density (D) = 8.12; V × D = 11.48.			
CV (%)	5.9			

Means sharing at least one common lowercase letter within the same statistical comparison are not significantly different at the 5% probability level.

3.2. Effect of Cultivar and Plant Density on Mean Quinoa Panicle Length

The results showed similar mean panicle lengths for the two cultivars. Giza-1 had a mean panicle length of 16.78 cm, compared with 16.64 cm for Red Carina, a difference of only 0.14 cm. This difference was smaller than the least significant difference (LSD) for cultivar, indicating no statistically significant difference between the cultivars for this trait under the experimental conditions.

Regarding plant density, treatment D2, corresponding to a within-row spacing of 15 cm, recorded the highest mean panicle length of 17.42 cm. This was followed by D1, at 10-cm spacing, with a mean of 16.38 cm, whereas D3, at 20-cm spacing, recorded the lowest mean of 16.33 cm. Despite these numerical differences, the differences among plant density means did not exceed the LSD value of 1.797 cm, indicating no significant effect of plant density on panicle length at the 5% probability level.

For the cultivar $\times$ plant density interaction, Red Carina under D2 recorded the greatest mean panicle length, at 17.67 cm, whereas the same cultivar under D3 recorded the lowest mean, at 15.83 cm. Nevertheless, the differences among treatment means did not reach statistical significance according to the letter groupings presented in the table and the LSD for the interaction. Thus, the numerical differences do not provide sufficient statistical evidence that the two cultivars responded differently to the plant density levels investigated.

Overall, the grand mean panicle length was 16.71 cm. The results indicate that the two cultivars were similar and that plant density treatments did not differ significantly for this trait under the experimental conditions. This may reflect a limited response of panicle length to variation in plant density within the spacing range investigated. However, confirming this interpretation requires comparison with previous studies and other growth- and yield-related traits.

Table 3. Effects of cultivar and plant density on mean quinoa panicle length (cm) during the 2024/2025 and 2025/2026 growing seasons

Cultivar	D1 (10 $\times$ 30 cm)	D2 (15 $\times$ 30 cm)	D3 (20 $\times$ 30 cm)	Cultivar mean
Giza-1	16.33 a	17.17 a	16.83 a	16.78 a
Red Carina	16.43 a	17.67 a	15.83 a	16.64 a
Plant density mean	16.38 a	17.42 a	16.33 a	16.71
LSD (0.05)	Cultivar (V) = 1.47; Density (D) = 1.80; V $\times$ D = 2.54			
CV (%)	8.5			

Means sharing at least one common lowercase letter within the same statistical comparison are not significantly different at the 5% probability level.

3.3. Effect of Cultivar and Plant Density on Mean Grain Weight per Quinoa Plant

The results revealed significant differences in mean grain weight per plant attributable to cultivar and plant density. The interaction between these factors also showed significant differences in the responses of the two cultivars to the treatments investigated.

Red Carina significantly outperformed Giza-1 in grain weight per plant, with a mean of 34.84 g compared with 23.03 g for Giza-1. This represented an increase of 11.81 g, or approximately 51.3%. This finding indicates differences in individual-plant productivity between the cultivars under the experimental conditions and may be associated with their genetic characteristics and their respective capacities to produce inflorescences and grains and support grain filling. However, identifying the mechanisms responsible for this superiority requires consideration of other yield components.

Treatment D3, corresponding to a within-row spacing of 20 cm, recorded the highest mean grain weight per plant, at 31.93 g. This was followed by D1, at 10-cm spacing, with 28.39 g, whereas D2, at 15-cm spacing, recorded the lowest mean of 26.49 g. Differences among the means were significant according to the LSD value for plant density of 0.989 g.

These results indicate that increasing within-row spacing from 15 to 20 cm was associated with a significant increase in grain weight per plant. This may be explained by reduced competition among plants for light, water, and nutrients, potentially allowing individual plants to produce more grains or

improve grain filling. However, this remains a possible explanation and cannot be established from grain weight alone without data on grain number and other yield components.

The general trend is consistent with the findings of Wang et al. (2020), who reported higher grain weight per quinoa plant at lower plant densities than at higher densities under their experimental conditions. Nevertheless, differences in density levels and growing conditions between the two studies should be considered when making comparisons.

The cultivar $\times$ plant density interaction revealed clear significant differences. Red Carina under D3 achieved the highest mean grain weight per plant, at 41.32 g, and was assigned to statistical group (a). In contrast, Giza-1 under D2 recorded the lowest mean of 22.28 g, belonging to group (e).

For Red Carina, grain weight per plant increased from 30.69 g at D2 to 41.32 g at D3, an increase of 10.63 g, or approximately 34.6%. Giza-1, however, recorded its highest mean at D1, at 24.26 g, followed by 22.28 g at D2 and 22.54 g at D3. These findings indicate that the response of grain weight per plant to changes in spacing was not uniform across the two cultivars. Red Carina performed best at the widest spacing, whereas Giza-1 recorded its highest value at the narrowest spacing.

This interaction highlights the importance of selecting an appropriate planting spacing for each cultivar rather than assuming a uniform response across cultivars. Under the conditions of the present study, combining Red Carina with a 20-cm within-row spacing appears promising for maximizing individual-plant grain production.

However, an important agronomic distinction must be emphasized: greater grain weight per plant does not necessarily translate into higher grain yield per unit area. At higher plant densities, the increased number of plants per unit area may compensate for lower individual-plant productivity. Therefore, this result must be interpreted alongside grain yield per hectare before identifying the best treatment in terms of overall agronomic productivity.

Table 4. Effects of cultivar and plant density on mean grain weight per quinoa plant (g) during the 2024/2025 and 2025/2026 growing seasons

Cultivar	D1 (10 $\times$ 30 cm)	D2 (15 $\times$ 30 cm)	D3 (20 $\times$ 30 cm)	Cultivar mean
Giza-1	24.26 d	22.28 e	22.54 e	23.03 b
Red Carina	32.52 b	30.69 c	41.32 a	34.84 a
Plant density mean	28.39 b	26.49 c	31.93 a	28.94
LSD (0.05)	Cultivar (V) = 1.40; Density (D) = 0.99; V $\times$ D = 0.81.			
CV (%)	2.7			

Means sharing at least one common lowercase letter within the same statistical comparison are not significantly different at the 5% probability level.

3.4. Effect of Cultivar and Plant Density on Mean Quinoa Stem Diameter

The results revealed significant differences in mean quinoa stem diameter according to cultivar and plant density. The interaction between the two factors also indicated differences in the responses of the cultivars to the treatments investigated.

Red Carina significantly outperformed Giza-1 in mean stem diameter, recording 0.914 cm compared with 0.661 cm for Giza-1. This represented an increase of 0.253 cm, or approximately 38.3%. This finding indicates differences between the cultivars in stem development and structural characteristics, potentially associated with their genetic variation in vegetative growth habit. Stem diameter is an important morphological trait; however, a larger diameter alone cannot be considered conclusive evidence of greater lodging resistance unless lodging resistance is measured directly.

Mean stem diameter increased progressively from 0.696 cm at D1, corresponding to a within-row spacing of 10 cm, to 0.775 cm at D2, at 15-cm spacing, and then to 0.892 cm at D3, at 20-cm spacing. The difference between D3 and D1 was approximately 0.196 cm, exceeding the LSD for plant density of 0.1333 cm; therefore, the difference between these treatments was significant. In contrast, the differences between D1 and D2 and between D2 and D3 were not significant.

These findings indicate that wider within-row spacing, accompanied by lower plant density, was associated with greater stem diameter under the experimental conditions. This may be attributed to reduced competition for light and other available resources, potentially allowing the development of thicker stems. The general trend is consistent with Asher et al. (2022), who reported a positive association between wider inter-row spacing and quinoa stem diameter under their experimental conditions. However, because the spacing treatments and environmental conditions differed between the studies, the comparison should be restricted to the general trend rather than assuming quantitatively identical responses.

The cultivar $\times$ plant density interaction showed that the largest mean stem diameter was recorded for Red Carina under D3, at 1.167 cm, belonging to statistical group (a). In contrast, the smallest mean was recorded for Giza-1 under D3, at 0.617 cm, belonging to group (c).

For Red Carina, stem diameter increased from 0.743 cm at D1 to 1.167 cm at D3, an increase of 0.424 cm, or approximately 57.1%. Giza-1 did not exhibit the same pattern; its highest value was recorded at D2, with a mean of 0.717 cm, whereas its lowest value occurred at D3, at 0.617 cm. These results suggest that the two cultivars responded differently to changes in plant spacing, with a more pronounced response in Red Carina at the widest spacing.

From an agronomic perspective, the combination of Red Carina and D3 produced the greatest stem diameter in this experiment. However, identifying the most suitable treatment for cultivation requires considering other traits, including grain weight per plant, grain yield per unit area, and lodging resistance, because greater stem diameter does not necessarily correspond to the highest economic yield.

Table 5. Effects of cultivar and plant density on mean quinoa stem diameter (cm) during the 2024/2025 and 2025/2026 growing seasons

Cultivar	D1 (10 × 30 cm)	D2 (15 × 30 cm)	D3 (20 × 30 cm)	Cultivar mean
Giza-1	0.650 bc	0.717 bc	0.617 c	0.661 b
Red Carina	0.743 bc	0.833 b	1.167 a	0.914 a
Plant density mean	0.696 b	0.775 ab	0.892 a	0.790
LSD (0.05)	Cultivar (V) = 0.11; Density (D) = 0.13; V × D = 0.19			
CV (%)	2.7			

Means sharing at least one common lowercase letter within the same statistical comparison are not significantly different at the 5% probability level.

3.5. Effect of Cultivar and Plant Density on Mean Quinoa Grain Yield

The results revealed significant differences in mean grain yield between the two cultivars. Red Carina outperformed Giza-1, with a mean yield of 1.665 t ha⁻¹ compared with 1.373 t ha⁻¹ for Giza-1, representing an increase of approximately 21.3%. This indicates differences in the productive potential of the two cultivars under the experimental conditions. However, this superiority should be considered alongside other yield-related traits and the results from both growing seasons to assess its consistency.

Regarding plant density, D3, which represented the widest within-row spacing and the lowest plant density, recorded the highest mean grain yield of 2.172 t ha⁻¹. This was significantly higher than the yields recorded under D2 and D1, which were 1.255 and 1.129 t ha⁻¹, respectively. The increase in mean grain yield under D3 was approximately 92.3% compared with D1. This may indicate that reduced competition among plants for light, water, and nutrients improved grain production under the conditions of this experiment. Nevertheless, this finding should be interpreted in the context of the experimental site, growing seasons, and cultivars, as quinoa responses to plant density may vary with environmental conditions and crop management practices.

Regarding the cultivar × plant density interaction, Red Carina × D3 produced the highest grain yield, at 2.837 t ha⁻¹, significantly exceeding all other treatments according to the interaction LSD. In contrast, Red Carina × D2 recorded the lowest value, at 1.041 t ha⁻¹, although it did not differ significantly from Red Carina × D1, which yielded 1.116 t ha⁻¹. The difference between these treatments was 0.075 t ha⁻¹, below the interaction LSD of 0.088 t ha⁻¹.

These results demonstrate that Red Carina responded differently across plant density levels. Its grain yield increased markedly under D3, whereas no significant difference was observed between D1 and D2. For Giza-1, grain yield increased from 1.142 t ha⁻¹ under D1 to 1.470 t ha⁻¹ under D2 and 1.506 t ha⁻¹ under D3, with no significant difference between D2 and D3. This further supports the importance of selecting an appropriate plant density for each cultivar rather than assuming a uniform response across cultivars.

The importance of plant density in determining grain yield is consistent with the subject investigated by Asher et al. (2022), who evaluated the effects of inter-row spacing on quinoa growth and yield under Mediterranean climatic conditions and showed that grain yield responses to spacing were influenced by growing conditions and the genetic materials investigated. Keskin and Önkür (2019) also examined the effects of inter-row and within-row spacing on quinoa seed yield and certain plant traits, highlighting the importance of identifying suitable planting distances for local environmental conditions.

Nevertheless, the findings of these studies cannot necessarily be expected to match those of the present experiment because of differences in cultivars, spacing treatments, and growing conditions. The principal conclusion from the present data is that D3 produced the highest mean grain yield, with particularly pronounced superiority in Red Carina. The practical suitability of this treatment should be further evaluated using results from both growing seasons, production costs, and the other traits investigated.

Table 6. Effects of cultivar and plant density on mean quinoa grain yield (t ha⁻¹) during the 2024/2025 and 2025/2026 growing seasons

Cultivar	D1 (10 × 30 cm)	D2 (15 × 30 cm)	D3 (20 × 30 cm)	Cultivar mean
Giza-1	1.142 c	1.470 b	1.506 b	1.373 b
Red Carina	1.116 cd	1.041 d	2.837 a	1.665 a
Plant density mean	1.129 c	1.255 b	2.172 a	1.519
LSD (0.05)	Cultivar (V) = 0.051; Density (D) = 0.062; V × D = 0.088			
CV (%)	2.7			

Means sharing at least one common lowercase letter within the same statistical comparison are not significantly different at the 5% probability level.

3.6. Effect of Cultivar and Plant Density on Mean Quinoa Biological Yield

The results showed no significant difference between the two cultivars in mean biological yield. Giza-1 recorded a mean biological yield of approximately 9.26 t ha⁻¹, whereas Red Carina recorded 9.39 t ha⁻¹. Although Red Carina had a numerically higher yield by 0.13 t ha⁻¹, this difference did not reach statistical significance according to the LSD value of 0.646. This may indicate similar total biomass production by the two cultivars under the experimental conditions, despite differences in their responses to plant density.

Regarding plant density, significant differences were observed among the three density levels. D3 recorded the highest mean biological yield, at 13.78 t ha⁻¹, followed by D2, at 8.28 t ha⁻¹, whereas D1 recorded the lowest mean of 5.91 t ha⁻¹. D3 significantly exceeded both D1 and D2, and D2 also significantly exceeded D1. Biological yield under D3 increased by approximately 133.2% compared with D1.

This increase may be associated with improved plant growth and dry matter accumulation when plants were provided with more space, potentially reducing competition for light, water, and nutrients.

However, this response should not be generalized to all agricultural environments, as biological yield is influenced by plant density, cultivar, environmental conditions, and crop management.

Regarding the cultivar $\times$ plant density interaction, Red Carina $\times$ D3 recorded the highest mean biological yield, at 17.38 t ha⁻¹, significantly exceeding the other treatments. Conversely, Red Carina $\times$ D1 recorded the lowest mean, at 3.80 t ha⁻¹. This demonstrates a pronounced response of Red Carina to changes in plant density, with biological yield increasing from 3.80 t ha⁻¹ under D1 to 17.38 t ha⁻¹ under D3.

For Giza-1, biological yield increased from 8.02 t ha⁻¹ under D1 to 9.59 t ha⁻¹ under D2 and 10.18 t ha⁻¹ under D3. The difference between D2 and D3 was not significant, whereas both treatments significantly exceeded D1. These results suggest that the response of biological yield to plant density differed between cultivars and that the pronounced numerical superiority of Red Carina under D3 contributed to the interaction between the two factors.

Overall, D3 produced the highest biological yield in both cultivars, with a more pronounced effect in Red Carina. Nevertheless, this result should be interpreted together with grain yield because greater biological yield does not necessarily translate into a proportional increase in grain yield. The relationship depends partly on how dry matter is partitioned between vegetative and reproductive plant components.

Table 7. Effects of cultivar and plant density on mean quinoa biological yield (t ha⁻¹) during the 2024/2025 and 2025/2026 growing seasons

Cultivar	D1 (10 $\times$ 30 cm)	D2 (15 $\times$ 30 cm)	D3 (20 $\times$ 30 cm)	Cultivar mean
Giza-1	8.02 c	9.59 b	10.18 b	9.26 a
Red Carina	3.80 d	6.98 c	17.38 a	9.39 a
Plant density mean	5.91 c	8.28 b	13.78 a	9.32
LSD (0.05)	Cultivar (V) = 0.65; Density (D) = 0.79; V $\times$ D = 1.12			
CV (%)	2.7			

Means sharing at least one common lowercase letter within the same statistical comparison are not significantly different at the 5% probability level.

3.7. Effect of Cultivar and Plant Density on Quinoa Harvest Index

The results revealed significant differences between the two cultivars in mean harvest index. Red Carina significantly outperformed Giza-1, with a mean harvest index of 20.25% compared with 15.21% for Giza-1, representing a relative increase of approximately 33.1%. This indicates differences between the cultivars in the proportion of total biological yield allocated to grain production. A higher harvest index may be associated with more efficient allocation of dry matter to reproductive organs; however, identifying the underlying mechanism requires additional physiological and yield-related measurements.

Regarding plant density, D1 recorded the highest mean harvest index, at 21.90%, significantly exceeding both D2 and D3, which recorded 15.73% and 15.56%, respectively. No significant difference was observed between D2 and D3. These results indicate that plants grown under D1 had, on average, a higher grain-yield-to-biological-yield ratio. Nevertheless, a higher harvest index does not necessarily imply a higher absolute grain yield because this index is influenced by both grain yield and biological yield.

For the cultivar $\times$ plant density interaction, Red Carina $\times$ D1 recorded the highest harvest index, at 29.48%, significantly exceeding the other treatments, whose values ranged from 14.33% to 16.51%. The harvest index of Red Carina decreased from 29.48% under D1 to 14.96% under D2, before increasing slightly to 16.32% under D3. In contrast, the harvest index of Giza-1 ranged from 14.33% to 16.51%, with no significant differences among its three plant density treatments according to the statistical letter groupings.

The high harvest index recorded for Red Carina $\times$ D1 may be attributable to lower total biological yield relative to grain yield, rather than necessarily reflecting an increase in grain yield itself. This interpretation becomes clearer when the results are compared with those for grain and biological yields. This treatment produced a grain yield of 1.116 t ha⁻¹ and a biological yield of 3.80 t ha⁻¹, whereas Red Carina $\times$ D3 produced a much higher grain yield of 2.837 t ha⁻¹ despite having a lower harvest index of 16.32%.

Accordingly, the highest harvest index was recorded for Red Carina $\times$ D1, whereas the highest grain and biological yields were obtained with Red Carina $\times$ D3. This demonstrates why harvest index should not be used alone to identify the most productive treatment. Instead, it should be interpreted together with grain yield and biological yield in relation to the intended production objective.

Table 8. Effects of cultivar and plant density on mean quinoa harvest index (%) during the 2024/2025 and 2025/2026 growing seasons

Cultivar	D1 (10 $\times$ 30 cm)	D2 (15 $\times$ 30 cm)	D3 (20 $\times$ 30 cm)	Cultivar mean
Giza-1	14.33 b	16.51 b	14.80 b	15.21 b
Red Carina	29.48 a	14.96 b	16.32 b	20.25 a
Plant density mean	21.90 a	15.73 b	15.56 b	17.73
LSD (0.05)	Cultivar (V) = 1.97; Density (D) = 2.41; V $\times$ D = 3.41			
CV (%)	2.7			

Means sharing at least one common lowercase letter within the same statistical comparison are not significantly different at the 5% probability level.

5. Conclusion

1. Red Carina outperformed Giza-1 in grain yield, grain weight per plant, plant height, and stem diameter, whereas no significant differences were observed between the cultivars in panicle length or biological yield.
2. A within-row spacing of 20 cm (D3) produced the highest mean grain yield, biological yield, and grain weight per plant.
3. Red Carina $\times$ D3 recorded the highest grain yield, at 2.837 t ha⁻¹, whereas Red Carina $\times$ D1 achieved the highest harvest index, at 29.48%.

5. Recommendations

1. Further evaluate Red Carina at a within-row spacing of 20 cm across different growing seasons and locations.
2. Conduct an economic assessment of the investigated treatments before formulating a final agronomic recommendation.
3. Extend the evaluation of yield-related and quality traits to identify the most suitable treatment according to the intended production objective.

6. References

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