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Effect of sowing date and plant density on seed yield and yield attributes of quinoa (*Chenopodium quinoa*) genotypes

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ABSTRACT - Quinoa (*Chenopodium quinoa*) is world-renowned for its nutritional and health benefits and its adaptability to different environments. Despite some research on quinoa cultivation, determining the appropriate planting date and density for different genotypes and regions needs to be studied. The main objective of this study was to determine the effects of planting date and planting density on quinoa seed yield in climatic conditions of Kermanshah. In this regard, field experiments were conducted during two growing seasons (2019-2020) at the research farm of Razi University, Kermanshah, Iran. The experiments were conducted as split-plot factorial in randomized complete blocks design with three replications. Three sowing dates (March 15^{th}, April 15^{th}, and May 15^{th}) were assigned to the main plots, two planting densities (40 and 60 plants m^{-2}), and three genotypes including Titicaca, Q29, and Red Carina as subplots. The results showed that the highest seed yield (2179.72 and 2267.39 kg ha^{-1}) were achieved on April 15^{th}, 2019 and May 15^{th}, 2020, respectively. Sowing dates of April 15^{th} in 2019 and May 15^{th} in 2020 with a plant density of 60 plants m^{-2} and Titicaca genotype had the highest seed yield for quinoa in Kermanshah climatic conditions. The results showed that panicle length and biological yield had a positive and significant correlation with grain yield in all studied planting dates. There was a positive and significant correlation between grain yield and grain weight per plant, 1000-grain weight, and biological yield at both densities. The path analysis revealed that panicle length had the highest positive direct effect on seed yield followed by 1000-seed weight on the first sowing date in 2019 and 2020, while biological yield and panicle length had the highest positive direct effect on seed yield on the second and third sowing dates, respectively. This experiment showed that genotypes and planting dates are the most determining factors affecting quinoa growth, development, and yield compared with planting densities.

INTRODUCTION

Quinoa (*Chenopodium quinoa* Willd.) is a dicotyledonous plant that belongs to the Amaranthaceae family and grows mainly in South America in the Andes, including Colombia, Peru, Argentina, Chile, and Bolivia. It is currently cultivated on all continents (Präger et al., 2018). Quinoa is a C_3 plant that has been reported to be well adapted to the adverse conditions of the Andean highlands, has very high drought and frost tolerance, and is tolerant to salinity (Nurse et al., 2016). It is considered a pseudo-cereal that produces a grain-like seed, which can be sold as a whole grain or used in bread, soups, or other uses. In other words, it is a seed that is prepared and used as a grain (Awadalla and Morsy, 2017).

Dependence on natural resources and their consumption has increased due to the increase in the world population. In addition, there are many problems with adequate and balanced nutrition with increasing global warming (Altuner et al., 2019). However, humans were encouraged to find and develop new resources. The utilization of plant genotypes that increase yield and quality in animal and plant production has been mandatory in any climates and natural conditions (Timsina, 2018). Cereals such as wheat (*Triticum aestivum*) and rice (*Oryza sativa*) are the most important food sources in human nutrition, and they cause celiac disease (Scherf, 2019). Therefore, quinoa plays an essential role as an alternative plant that can be grown on a large scale (Sharma et al., 2015).

Quinoa seed has high protein content, ranging between 12 to 23% depending on genotype, which is higher than common grains but lower than oilseeds and legumes. Furthermore, quinoa is one of the few plant foods that contains nine essential amino acids (Dakhili et al., 2019). In addition, quinoa contains fiber, magnesium, vitamins B, iron, potassium, calcium, phosphorus, vitamin E. (Awadalla and Morsy, 2017).

The presence of poor-quality water resources is the main problem of agriculture in arid and semi-arid regions of Iran. Salty saline water has created many restrictions for agricultural development and utilization of water and soil resources. Cultivation tolerant or semi tolerant plant to salinity, drought, and optimal use of water and soil resources seems necessary (Pulido-Bosch et al., 2018). Planting date for some quinoa genotypes is the main factor playing a prominent role in its production. Variation in the germplasm of quinoa is evident in its response to planting date. (Hinojosa *et al.*, 2018). Sowing date has the most significant impact on the phonological and growth characteristics of plants compared to other crop traits (Jahanbkhsh et al., 2020). Nagib et al., 2020 showed significant effects of planting dates on quinoa yield and yield components, and the best growth and yield were recorded from sowing seeds in the middle of November. Nurse et al., 2016 revealed that when planting date varied from mid-May to late June, quinoa reached physiological maturity and produced yield, but the late planting date did not mature before the first frost, and yield decreased by more than 50%.

Planting density is a vital factor in determining the yield of crops. High planting densities increase intra-species competition resulting in yield reduction. On the other hand, in low planting densities, environmental facilities, including light, space, water, and soil, are not optimally used, ultimately reducing yield (Xia et al., 2019). Eisa et al., 2018 reported that planting density had a significant effect on the grain yield of quinoa, and the highest seed yield was obtained from the highest density (167,000 plants/ha), which was 34.7% higher than quinoa seed yield at a density of 56,000 plants/ha. In 2020, Van Minh *et al.* showed that the optimal planting density for quinoa is eight plants/m^2. Also, panicle length, number of panicle/plants, number of seeds/panicles, thousand-seed weight, seed yield, protein content, and ash content were significantly affected by plant density.

Quinoa is considered a drought-tolerant crop with high nutritional value and cold tolerance at the end of the season; therefore, determining the agronomic needs of this plant can play an influential role in its yield. Sowing date, planting density, and genotypes are essential factors affecting the seed yield and quality in Quinoa. Consequently, the main objectives of the present study were to establish, the effects of planting dates, genotype, and plant densities on seed yield of quinoa grown under climatic conditions of Kermanshah areas in western Iran.

MATERIALS AND METHODS

Field experiments were conducted during two growing seasons (2019-2020) at the Experimental Field of the Agricultural Faculty of Razi University, Kermanshah, Iran (longitude of 47° and 6′ E, latitude of 36° and 19′ N, and altitude of 1318 m). To determine the soil characteristics, soil chemical characteristics, and fertility conditions of the experimental site, soil samples were taken from 0-30 cm depth before planting genotypes of quinoa. Soil properties of the research field at the experiment site are shown in Table 1. The climate of the experimental region during both growing seasons of quinoa was obtained from the meteorological station of Kermanshah as shown in Table 2. The experiment was conducted as a split-plot factorial in randomized complete blocks design with three replications. The treatments were three sowing dates (March 15^{th}, April 15^{th}, and May 15^{th}) assigned to the main plots, two planting densities (40 and 60 plants m^{-2}), and three genotypes including Titicaca, Q29, and Red Carina as subplots. The characteristics of these quinoa genotypes are shown in Table 3.

Once in every year, 2000 kg ha^{-1} cattle manure was used, and the field was farrowed to a depth of 0.3 m with a disk plow to prepare seedbeds before sowing. Seedbeds up to 8 cm deep were prepared two days before sowing using a rotary harrow. The size of each plot was 4 m2 (3.20 m × 1.25 m), consisting of five rows with a distance of 0.25 m between rows. Planting was accomplished mechanically on three planting dates at a depth of 1 cm. Furthermore, planting was performed densely, and after the plants reached a height of 10-15 cm, the distances between the plants were maintained at 10 cm and 7 cm, respectively, for densities of 40 and 60 plants/m2 by thinning.

Table 1. Soil properties of the research field at the experiment site at 0-30 cm Soil depths

	Properties	Amount		Properties	Amount
Mechanical analysis	Clay (%)	42.0		N (%)	0.116
	Silt (%)	44.2		P (mg kg^{-1})	11.4
	Sand (%)	13.8	Nutrients	K (mg kg^{-1})	440
Chemical analysis	pH	7.75		Mn (mg kg^{-1})	4.8
	B.D (g cm^{-3})	1.30		Fe (mg kg^{-1})	3.23
	PWP (%)	18		Zn (mg kg^{-1})	1.03
	FC (%)	35		Cu (mg kg^{-1})	1.4
	Penetration (cm h^{-1})	1.00		B (mg kg^{-1})	0
	EC (mS cm^{-1})	0.83		Organic Carbon (%)	1.16

Table 2. Some meteorological parameters of the experimental region during the growing seasons of quinoa in this study

Months	2018-2019 growing season			2019-2020 growing season		
	Average Temperature (°C)		Average Precipitation (mm)	Average Temperature (°C)		Average Precipitation (mm)
	Minimum	Maximum		Minimum	Maximum	
March	0.1	12.2	79.1	3.7	16.7	148.2
April	4.7	16.2	194.8	4.5	18.0	93.3
May	6.6	24.4	17.5	9.4	25.4	40.1
June	13.0	34.0	0	13.2	34.5	0
July	16.6	38.7	0	17.6	37.5	0
August	18.6	39.5	0	18.2	38.9	0
October	14.4	35.3	0	14.7	35.5	0
November	11.0	30.5	15.4	9.0	29.0	0.8

Table 3. The characteristics of three quinoa genotypes including Titicaca, Q29, and Red Carina

Genotypes	Titicaca	Q29	Red Carina
Origin	Denmark	Chile	The Netherlands
Maturity	early	Average	Late
Sensitivity to the length of the day	Neutral day	Neutral day	Neutral day
The average weight of a thousand seeds (g)	2	2.6	2.4
Average plant height (cm)	112	128	131
The amount of saponin (mg/g)	4.7	5.1	5.2
Seed color	Light cream	Light cream	Light cream

In the experiments of this study, irrigation was done once a week in the form of rain, and the experimental field was controlled for weeds by hand four weeks after emergence during vegetative growth, and this operation was repeated three times.

Harvest dates for each genotype were set following plant maturity for each sowing dates (Ciriello *et al.*, 2021) as stage 99 according to the extended BBCH scale (Sosa-Zuniga et al., 2017). To avoid marginal effects, half meters from the top and bottom of each plot were removed. The plots were hand-harvested at a 2.20 m section of three central rows for each plot to determine the plant height, panicle length, number of seeds per plant, and the weight of seeds per plant, thousand-seed weight, seed yield, biological yield, and harvest index. An average of four thousand seeds weight was measured to obtain the thousand-seed weight. Five plants from each plot were randomly selected to determine plant height and seeds per plant. After drying the collected seeds for 24-48 hours at 75-80 ° C, other measurements were conducted and reported based on the dry weight.

The collected data from the first and second years were analyzed using SAS software version 9.1 (SAS Institute, Cary NC), and the means were compared based on the least significant difference (LSD) test at ($P \leq 0.01$) and ($P \leq 0.05$). Planting date, planting density, and genotype were fixed effects and years were considered random effects. Pearson's correlation between studied traits and path analysis was performed according to the method explained by Dewey and Lu (1959) using SPSS 16.0 Statistical Software (SPSS Inc., Chicago, Ill., USA).

RESULTS AND DISCUSSION

The results of combined ANOVA showed significant differences between sowing dates, planting densities, and genotypes. The LSD test was run only on the following interactions considering the significance of the two, three, and four-way interactions:

Plant Height

The analysis of variance showed that the effects of years, sowing dates, planting densities, genotypes, and their interactions were significant for plant height (Table 4). Plant height increased with delayed sowing date in 2019; however, in 2020, plant height increased with delayed sowing date only from March 15th to April 15th and decreased with delaying sowing date from April 15th to May 15th. The highest plant height (148.608 cm) was obtained with a sowing date of April 15th, 2020 (Fig. 1). The delay in the planting date led to the collision of the vegetative stage with optimal growth temperature conditions (15 to 25 °C) and consequently increased vegetative growth. Whereas in early planting dates, plant exposure to low-temperature conditions leads to plant stress exposure, and therefore in the path of shortening the vegetative phase and faster entry into the reproductive phase and plant height decreases. Mahmoud (2017) reported that quinoa showed the highest plant height (146.0 cm) on December 25th, 2015, compared with December 9th (135.3 cm) and January 19th (121.3 cm) sowing dates in Egypt. Temel and Yolcu (2020) reported that quinoa growth time shortens with increasing temperature. Therefore, plants may mature in late planting without sufficient vegetative growth so that the plant height may be shorter in late planting.

The highest plant height (163.627 and 108.667 cm) was recorded with the "Q29" genotype and April 15th in 2019 and 2020 sowing dates, respectively (Table 5). Altuner et al. (2019) reported that different planting dates significantly affected plant height in quinoa genotypes. They showed that the plant height of Valiente and Titicaca genotypes were 86.9 cm and 72.9 cm, respectively. Ramesh (2016) pointed out that environmental factors such as temperature and rainfall play an essential role in plant height. In addition, studies on quinoa have reported that plant height varies depending on environmental conditions, resulting in a decrease in plant height with delayed planting dates. (Casini, 2019).

Panicle length

The effects of years, sowing dates, planting densities, genotypes, and their interactions, were significant for panicle length (Table 4). Panicle length increased with delayed sowing date from March 15th to April 15th and, decreased with delayed planting from April 15th to May 15th in 2019 but increased with delayed sowing date from March 15th to May 15th in 2020. The highest panicle length was obtained (17.563 cm) with a sowing date of April 15th, planting density of 60 plants/m^2, and Titicaca genotype in 2019 (Fig. 2). The lowest panicle length was obtained with the sowing date of March 15th, the density of 40 plants m^{-2}, and the Q29 genotype in the 2019 growing season (Fig. 2). Altuner et al. (2019) reported that the genotype and genotype × sowing date interactions were significant for the quinoa plant. The highest (42.8 cm) and lowest (31.1 cm) panicle lengths were recorded for the Valiente genotype on April 15th and Titicaca genotype on March 15th planting dates, respectively (Altuner et al., 2019). Ramesh et al. (2016) reported that the most extended quinoa panicle length was obtained on October 15th compared to planting dates of November 1st and November 16th.

Seed Numbers/Plant

The number of seeds per plant was significantly affected by year, sowing dates, planting densities, genotypes, and their interactions (Table 4). Delayed sowing from March 15th to April 15th increased seed numbers per plant and then from April 15th to May 15th decreased it in 2019. Nevertheless, in 2020, delayed sowing from March 15th to May 15th increased seed numbers per plant. The highest seed numbers per plant (2674.778 and 2550.11) were recorded on the sowing dates of May 15th in 2020, and April 15th in 2019, respectively (Table 6). Altuner et al. (2019) reported that the highest and lowest seed numbers/plant were obtained on the sowing dates of April 15th and March 15th, respectively. On the contrary, Isobe et al. (2016) found that the seed numbers per plant were significantly higher on the March sowing date than those on the other June and August sowing dates.

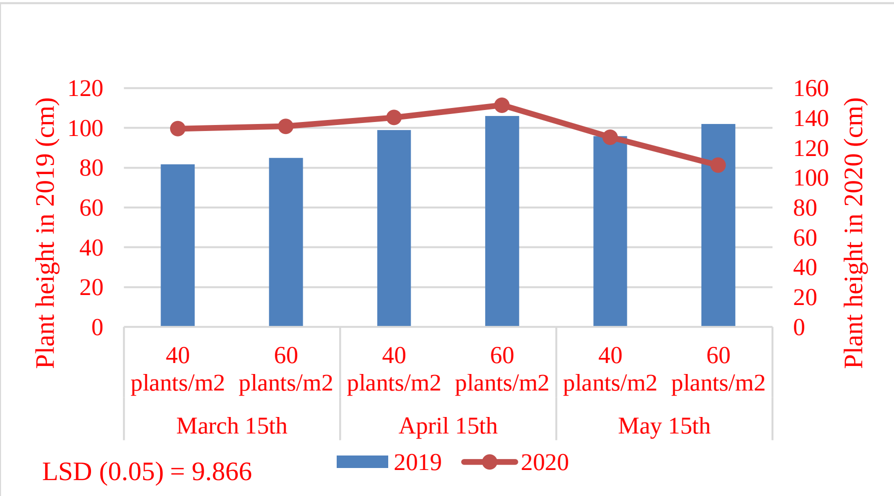

Fig 1. The effects of year× sowing date × plant density on quinoa plant height

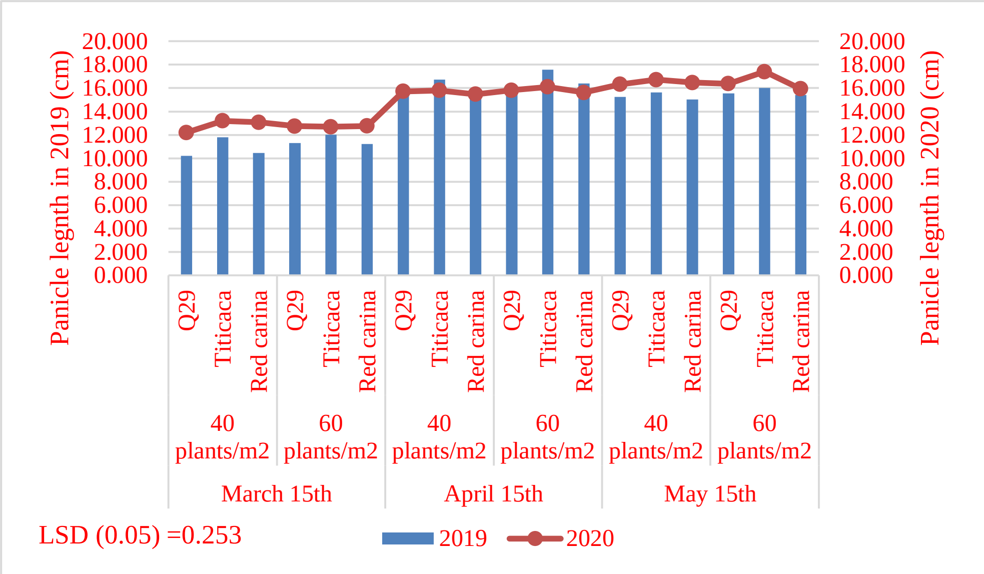

Fig 2. The effects of year × sowing date × plant density and genotype on panicle length of quinoa

Table 4. Combined ANOVA analysis for quinoa traits during 2019-2020 growing seasons

Sources of Variation	df	Plant height	Panicle length	Seed no./plant	Seed weight /plant	1000 seeds weight	Seed yield	Biological yield	Harvest index
Year (Y)	1	37119.31**	13.40**	9530136.33**	33.95**	5.13**	398337.79**	740364.48**	25.04**
(Rep×Y)	4	394.82*	0.11**	4047.02^{ns}	0.02^{ns}	0.01^{ns}	3963.59*	38241.65*	3.04^{ns}
Sowing date (SD)	2	2718.53**	196.63**	1169160.73**	17.60**	6.75**	3421588.26**	22217402.68**	45.62**
(SD×Y)	2	2388.69**	11.51**	1978286.58**	0.69**	0.38**	171405.48**	1679522.90**	60.62**
Error 1	8	387.76	0.02	6966.71	0.01	0.02	2485.70	65234.16	4.98
Density (D)	1	42.36^{ns}	2.26**	1695008.33**	13.12**	0.16**	62833.56**	1140422.26**	27.00**
(D×Y)	1	479.48*	1.49**	1862306.70**	14.95**	0.27**	23437.78**	455780.15**	10.70*
(SD×D)	2	449.21*	0.05*	4248.86^{ns}	0.17**	0.01^{ns}	327.15^{ns}	26991.68^{ns}	3.69^{ns}
(SD×D×Y)	2	462.28*	0.16**	8956.23^{ns}	0.14^{ns}	0.01^{ns}	2849.93^{ns}	4538.90^{ns}	2.40^{ns}
Genotype(G)	2	3233.94**	5.90**	108352.23**	0.38**	0.64**	81289.84**	1698456.26**	45.89**
(G×Y)	2	742.24**	0.80**	291814.19**	0.07**	0.40**	21699.73**	708188.93**	33.12**
(SD×G)	4	350.12*	0.15**	9281.04^{ns}	0.03**	0.02^{ns}	6682.04**	79319.04**	8.70**
(SD×G×Y)	4	301.59*	0.65**	4014.61^{ns}	0.06**	0.02*	12277.26**	35329.59^{ns}	2.39**
(D×G)	2	11.83^{ns}	0.09**	4863.25^{ns}	0.01^{ns}	0.00^{ns}	722.07^{ns}	2523.37^{ns}	2.58^{ns}
(D×G×Y)	2	44.95^{ns}	0.20**	8261.17^{ns}	0.01^{ns}	0.00^{ns}	1006.18^{ns}	5402.70^{ns}	0.18^{ns}
(SD×D×G)	4	196.78^{ns}	0.53**	7053.61^{ns}	0.02^{ns}	0.00^{ns}	3340.15^{ns}	22397.54^{ns}	1.61^{ns}
(SD×D×G×Y)	4	137.98^{ns}	0.09**	6603.37^{ns}	0.01^{ns}	0.01^{ns}	1366.32^{ns}	24777.20^{ns}	2.54^{ns}
Error 2	60	109.51	0.01	8458.03	0.01	0.44	1465.31	14216.61	1.65
C.V(%)		9.22	0.71	4.33	1.97	3.53	1.92	2.65	2.88

ns, * and **: No significant, significant at 5% and 1% probability level, respectively.

Seed Weight/Plant

The effects of years, sowing dates, planting densities, genotypes, and their interactions were significant for seed weight/plant (Table 4). Seed weight/plant increased with delayed sowing date from March 15th to May 15th in both years, with no significant difference between April 15th and May 15th sowing dates. The highest seed weight/plant (5.796 and 4.755 g) were recorded in Titicaca genotype with the sowing date of May 15th in 2020, and the Titicaca genotype with the sowing date of April 15th in 2019, respectively (Table 5). A similar result was obtained by Dao et al. (2020), who reported that seed weight/plant of different genotypes of quinoa was significantly different so that it was higher (7.58 g/plant) in the “Titicaca” genotype than those (0.60 and 0.15 g/plant) in Negra Collana and Pasankalla genotypes, respectively. Isobe *et al.* (2016) reported that March is the optimum sowing date in south Kanto, Japan, to get a high seed yield of quinoa. Shoman (2018) determined that December 1st is the optimum planting date in the Desert Research Center (D.R.C.), Agricultural Experiment Station at EL-Kharga Oasis, New Valley Governorate (27°47.7 42 N, 30°24.7 63 E) for obtaining the highest seed weight/plant compared with October 1st and November 1st sowing dates. Moreover, Nagib et al. (2020) reported that the heaviest seed weight/plant was produced in the middle of November sowing date.

Thousand-Seed Weight

The effects of sowing dates, planting densities, genotypes, years, and their interactions were significant for the thousand-seed weight (Table 4). Thousand-seed weight increased with delayed sowing date from March 15th to May 15th in both years. The highest thousand-seed weights (3.042 and 3.005 g) were obtained in the Titicaca genotype and the May 15th sowing date in 2019 and 2020, respectively. The lowest thousand-seed weights (1.57 and 2.19 g in 2019 and 2020, respectively) were recorded in the Q29 genotype and the March 15th sowing date in both years (Table 5). Altuner et al. (2019) pointed out that the effect of planting date on 1000-seed weight in quinoa genotypes was not significant. Moreover. Hamza et al. (2021) reported that quinoa sown on November 14th had a significantly higher thousand-seed weight (2.9 g) than those on earlier and later sowing dates.

Seed Yield

The effects of year, sowing dates, planting densities, genotypes, and their interactions were significant for seed yield (Table 4). Delaying planting in both cases increased seed yield in 2020; however, in 2019 it increased when the sowing date was delayed from March 15th to April 15th and decreased with the delayed sowing date from April 15th to May 15th. The highest seed yield (2267.389 and 2179.722 kg ha^{-1}) were achieved on May 15th, 2020, and April 15th, 2019, respectively (Table 6). It seems that the reason for increasing seed yield on the second and third planting dates is the optimum temperature in April and May, causing faster plant growth, more vigorous plants, and higher seed yield as suggested by Mirzaie et al. (2020). Lazaridi et al.(2020) reported that delayed planting reduced the yield of Andean lupin in Athens, Greece, due to limited plant life cycle by temperature and photoperiod.

Increasing planting density caused increased seed yield in both years. The highest seed yield (2054.407 and 1962.407 kg ha^{-1} in 2020 and 2019, respectively) was obtained with 60 plants m^{-2} (Table 6). The present study showed that the increase in seed yield per area was mainly attributed to branching reduction at the higher plant density, and therefore, a higher proportion of seed yield has been produced from the main panicle while lower plant density led to an increase in plant branching (Eisa et al., 2018). A similar result was reported by Eisa et al. (2018), who found that the seed yield significantly increased by 34.7% in the high rather than low planting density. On the contrary, Wang et al. (2020) found that increased quinoa planting density from 70.000 to 460.000 plants h^{-1} caused seed yield reduction in China.

Moreover, the interaction of planting dates, genotypes and years indicated that the highest seed yield (2318.333 and 2297.50 kg ha^{-1}) was obtained by Titicaca genotype on May 15th and April 15th sowing dates in 2020 and 2019, respectively. The lowest seed yield (1484.500 and 1689.167 kg ha^{-1} 2019 and 2020, respectively) was obtained by Red Carina and Q29 genotypes on March 15th, (Table 6). Similar results were reported by Altuner et al. (2019), who concluded that the highest seed yield of quinoa (134.5 g m^{-2}) and lowest (125.6 g m^{-2}) were obtained by the Valiente genotype of quinoa on April 15th and by Titicaca in March 15th sowing dates, respectively. Hamza *et al.* (2021) revealed that quinoa had a significantly higher seed yield (2063 kg ha^{-1}) when sown on November 14th than earlier and later sowing dates.

Table 5. The effects of year × sowing date × genotype on quinoa traits using the least significant difference (LSD) test

Year	Sowing date	Genotype	Plant height (cm)	Seed weight/plant (g)	1000-seed weight (g)	Seed yield (kg ha^{-1})	Harvest index (%)
2019	March 15th	Q29	87.75	3.14	1.57	1517.83	50.00
		Titicaca	82.66	3.30	1.91	1590.50	42.83
		Red carina	79.56	3.08	1.66	1484.50	48.16
	April 15th	Q29	108.66	4.29	1.92	2070.00	42.83
		Titicaca	102.76	4.75	2.42	2297.50	41.66
		Red carina	96.00	4.50	2.22	2171.66	44.33
	May 15th	Q29	103.93	4.24	2.46	2044.16	43.16
		Titicaca	97.65	4.42	3.04	2131.66	41.00
		Red carina	95.13	4.16	2.71	2004.16	44.00
2020	March 15th	Q29	153.90	4.22	2.19	1689.16	45.00
		Titicaca	134.73	4.34	2.25	1739.50	45.00
		Red carina	112.38	4.37	2.26	1748.33	45.00
	April 15th	Q29	163.62	5.35	2.77	2141.33	45.00
		Titicaca	144.38	5.39	2.79	2156.16	45.00
		Red carina	125.41	5.32	2.75	2128.50	45.00
	May 15th	Q29	120.39	5.63	2.92	2254.16	45.00
		Titicaca	116.93	5.79	3.00	2318.33	45.00
		Red carina	116.07	5.57	2.89	2229.66	46.66
Maximum			163.62	5.79	3.04	2318.33	50.00
Minimum			79.56	3.08	1.56	1484.50	42.83
Average			113.44	4.55	2.43	1984.28	44.70
LSD (0.05)			12.08	0.10	0.09	44.20	1.48

Table 6. The effects of year × sowing date and year × planting density interactions on quinoa traits using the least significant difference (LSD) test

Year	Sowing dates	Plant height (cm)	Seed number/ plant	Seed weight/ plant (g)	1000-seed weight (g)	Seed yield (kg ha^{-1})	Biological yield (kg ha^{-1})	Harvest index (%)
Sowing Date (SD)								
2019	March 15th	83.32	1853.16	3.17	1.71	1530.94	3286.94	47.00
	April 15th	102.47	2068.61	4.51	2.19	2179.72	5084.72	42.94
	May 15th	98.90	1565.77	4.27	2.73	2060.00	4832.05	42.72
2020	March 15th	133.67	2045.00	4.31	2.23	1725.66	4866.94	45.00
	April 15th	144.47	2550.11	5.35	2.77	2142.00	4802.66	45.00
	May 15th	117.79	2674.77	5.66	2.93	2267.38	5030.88	45.55
Maximum		144.47	2674.77	5.66	2.93	2267.38	5084.72	47.00
Minimum		83.32	1565.77	3.17	1.71	1530.94	3286.94	42.72
Average		113.44	2126.24	4.55	2.43	1984.28	4650.70	44.70
LSD (0.05)		15.13	64.15	0.08	0.11	38.32	196.32	1.71
Plant Density (D)								
2019	40 plant/m^2	92.17	2085.77	4.71	2.30	1884.70	4233.51	45.03
	60 plant/m^2	97.63	1572.59	3.27	2.12	1962.40	4568.96	43.40
2020	40 plant/m^2	133.46	2417.25	5.08	2.63	2035.63	4529.03	45.37
	60 plant/m^2	130.50	2429.33	5.13	2.66	2054.40	4604.63	45.00
Maximum		133.46	2429.33	5.13	2.66	2054.4	4604.63	45.37
Minimum		92.17	1572.59	3.27	2.12	1884.70	4233.51	43.40
Average		113.44	2126.24	4.55	2.43	1984.28	4484.03	44.70
LSD (0.05)		5.69	50.06	0.05	0.05	20.83	64.90	0.70

Biological Yield

The sowing dates, planting densities, genotypes, years, and their interactions significantly affected biological yield (Table 4). The highest (5084.250 kg ha^{-1}) and lowest (3418.50 kg ha^{-1}) biological yields were obtained by Titicaca genotype on the May 15th sowing date and by Q29 genotype on March 15th sowing date, respectively. Awadalla and Morsy (2017) and Wang et al. (2020) reported that the highest (4645.83 kg ha^{-1}) and lowest (3701.78 kg ha^{-1}) biological yields of quinoa were obtained by the Regalona genotype on November 1st and by Q52 genotype on October 1st sowing dates, respectively. Similar results were found by Öktem et al. (2021), who emphasized significant differences among planting dates for biomass yield of quinoa. Biomass yield ranged between 1281 kg dekare^{-1} (da^{-1}) and 1751.4 kg da^{-1} (one dekare is equal to 1000 square meters). The highest and lowest biomass yields were from the April 1st and February 15th sowing dates, respectively.

In the current study, increasing the planting density from 40 plants m^{-2} to 60 plants m^{-2} in both years increased biological yield, so that the highest biological yield (4604.630 and 4568.963 kg ha^{-1} in 2020 and 2019, respectively) was recorded with 60 plants m^{-2}. (Table 6). Zulkadir (2021) pointed out that the biological yield varied based on the differences between years, planting dates, and row spacing, and the difference between them in this trait was significant. According to the results of that study, the biological yield varied between 271.640 to 379.758 kg da^{-1} on May 11th and March 23th, respectively.

Harvest Index

The effects of years, sowing dates, planting densities, genotypes, and their interactions were significant for the harvest index (Table 4). In this study, the harvest index decreased with the delayed sowing dates in the 2019 growing season and no significant differences between sowing dates were observed in the 2020 growing season. The highest harvest index (50 %) was obtained by the Q29 genotype on the March 15th sowing date in the 2019 growing season (Table 5). Similar results were shown by Öktem *et al.* (2021), who reported significant differences in harvest index among quinoa sowing dates so that the highest harvest index was obtained on the April 15th sowing date. Hirich et al. (2014) stated that the harvest index decreased with the progression of planting times of quinoa in Morocco. Quinoa harvest indices were reported to be 30-57%, 48-59%, and 24-51% in Italy, Turkey, and Morocco ecological conditions, respectively (Lavini et al. 2014).

Analysis of Correlation Coefficients

A Person's correlation coefficient test was performed to analyze the correlation between variables (Tables 7 and 8). Other authors have used correlation analysis to examine the association of different traits in quinoa seeds (Granado-Rodríguez et al., 2021). The correlation analysis on different sowing dates determined that panicle length showed a significant positive correlation with seed yield and the biological yield on three sowing dates (March 15th, April 15th, and May 15th); however, there was a significant and negative correlation (-0.837*) between panicle length and harvest index in first sowing date (March 15th). Seed yield was significantly and positively correlated (0.933**, 0.937**, and 0.972**) with the biological yield on sowing dates of March 15th, April 15th, and May 15th, respectively (Table 7). Therefore, it seems that increasing biological yield naturally increases seed yield in quinoa.

In the current study, it has been also found that increasing biomass plays an influential role in increasing the seed yield in quinoa. A similar result was found by Bascuñán-Godoy *et al.* (2018), who reported that the highest seed yield correlated with biomass weight. Awadalla and Morsy (2017) reported that seed yield was negatively and significantly correlated with plant height, the weight of seed/plant, thousand-seed weight, and biological yield. In the current study. the correlation analysis revealed that seed yield (with the values of -0.830* and -0.883**) and biological yield (with the values of -0972** and -0.968**) were found significantly and negatively correlated with the harvest index, respectively, both on the sowing dates of March 15th and May 15th (Table 7). Similar results in the soybean plant were reported by Haghi et al., (2012). However, the opposite results were found by Hussain et al. (2020) and Algosaibi et al. (2021), who showed that the seed yield and harvest index of quinoa had significantly and positively correlated. In this study, the most effective relationships were those that were found between panicle length with the following traits including seed weight/plant (0.996** and 0.998**), 1000-seed weight (0.906** and 0.894**), seed yield (0.996** and 0.999**), biological yield (0.985** and 0.993**) of quinoa with considering planting densities of 40 plant m^{-2} and 60 plant m^{-2} for the first values and second values in aforementioned parentheses, respectively (Table 8). There was a significant and negative correlation (-0720* and -0.699*) between panicle length and harvest index for planting densities of 40 plant m^{-2} and 60 plant m^{-2}, respectively (Table 8).

In addition, highly positive and significant correlations were found among seed yield and the following traits including seed weight/plant (1.000** and 0.999**), thousand-seed weight (0.906* and 0.900*), biological yield (0.986** and 0.991**) in planting densities of 40 plants m^{-2} and 60 plants m^{-2}, respectively. Nevertheless, seed yield (-0.703* and -0.685*) and biological yield (-0.808** and -0.771**) had a significant and negative correlation with harvest index in planting densities of 40 plants m^{-2} and 60 plants m^{-2}, respectively (Table 8). Biomass does not increase in proportion to the increase in yield, so that if the seed yield increases by a unit, the biological yield will be increased by two units or more. Hunter et al. (2020) and Hussain *et al.* (2017) reported similar results in wheat.

Path Analysis

Path analysis showed that the correlation of the traits with the seed yield is due to their direct effects on yield or the results of the indirect effect through other traits. If the correlation of a trait with yield is due to the direct effect of that trait, there is a real relationship between them. However, if the correlation is due to the indirect effect of the trait via other traits, selection should be made on a trait that has had an indirect effect (Saba et al., 2018).

In the current study, it has been found that at the first planting date (March 15th), the most direct positive effect on seed yield belonged to panicle length, and the most negative direct effect was related to biological yield; however, the indirect effect of biological yield was positive through all other traits except plant height, which led to positive and strong correlation between biological yield and seed yield. Although the indirect effects of plant height through other traits on seed yield were negative, the direct effect was positive, reducing the correlation of these traits with seed yield. On the second (April 15th) and third (May 15th) planting dates, the most direct positive effect on yield belonged to biological yield (Table 9).

Table 7. The Pearson correlation coefficients of the quinoa traits under three sowing dates used in this study

Traits	Sowing dates	Plant height	Panicle length	Seed numbers /plant	Seed weight/ plant	1000-seed weight	Seed yield	Biological yield	Harvest index
Plant Height	SD1	1							
	SD2	1							
	SD3	1							
Panicle length	SD1	-0.351	1						
	SD2	0.016	1						
	SD3	-0.258	1						
Seed numbers/plant	SD1	-0.033	-0.530	1					
	SD2	-0.754	0.146	1					
	SD3	0.852	-0.205	1					
Seed weight/ plant	SD1	-0.211	-0.111	0.867*	1				
	SD2	-0.405	-0.202	0.666	1				
	SD3	0.690	-0.052	0.885	1				
1000-seed weight	SD1	-0.463	0.729	0.037	0.524	1			
	SD2	-0.595	0.588	0.701	0.581	1			
	SD3	-0.113	0.645	0.092	0.492	1			
Seed yield	SD1	-0.178	0.956**	-0.732	-0.378	0.527	1		
	SD2	-0.159	0.967**	0.159	-0.239	0.624	1		
	SD3	-0.331	0.955**	-0.336	-0.184	0.551	1		
Biological yield	SD1	-0.120	0.916*	-0.685	-0.248	0.662	0.933**	1	
	SD2	0.149	0.972**	-0.034	-0.221	0.533	0.937**	1	
	SD3	-0.343	0.862*	-0.414	-0.301	0.396	0.972**	1	
Harvest index	SD1	0.155	-0.837*	0.627	0.165	-0.706	-0.830*	-0.972**	1
	SD2	-0.623	-0.648	0.373	0.091	-0.224	-0.516	-0.782	1
	SD3	0.339	-0.707	0.463	0.376	-0.245	-0.883**	-0.968**	1

SD1: Sowing date one (March 15th), SD2: Sowing date two (April 15th), SD3: Sowing date three (May 15th).

Table 8. The Pearson correlation coefficients of quinoa traits under two plant densities used in this study

Traits	Sowing dates	Plant height	Panicle length	Seed numbers /plant	Seed weight/ plant	1000-seed weight	Seed yield	Biological yield	Harvest index
Plant Height	D1	1							
	D2	1							
Panicle length	D1	0.315	1						
	D2	0.224	1						
Seed numbers/plant	D1	0.588	0.728*	1					
	D2	-0.726*	-0.005	1					
Seed weight/ plant	D1	0.331	0.996**	0.732*	1				
	D2	0.177	0.998**	0.016	1				
1000-seed weight	D1	0.101	0.906**	0.387	0.906**	1			
	D2	-0.156	0.894**	0.224	0.916**	1			
Seed yield	D1	0.331	0.996**	0.732*	1.000**	0.906**	1		
	D2	0.204	0.999**	0.015	0.999**	0.900**	1		
Biological yield	D1	0.348	0.985**	0.727*	0.986**	0.883**	0.986**	1	
	D2	0.205	0.993**	-0.008	0.991**	0.915**	0.991**	1	
Harvest index	D1	-0.251	-0.720*	-0.514	-0.703*	-0.604	-0.703*	-0.808**	1
	D2	-0.123	-0.699	0.120	-0.688*	-0.731*	-0.685*	-0.771*	1

D1: Density one (40 plant/m^2) and D2: Density two (60 plant/m^2).

Table 9. Path coefficient analysis of sowing dates showing direct and indirect effects of traits on seed yield in quinoa

Sowing Date	Plant Traits	Direct effect	Indirect effects					
			PH	PL	SN	TSW	BY	r
March 15th	Plant Height	0.22		-0.39	0.02	-0.08	0.06	-0.18
	Panicle Length	1.12	-0.08		0.26	0.13	-0.48*	0.96**
	Seeds Number	-0.49	-0.01	-0.59		0.01	0.36	-0.73
	1000 Seed Weight	0.17	-0.10	0.82	-0.02		-0.35	0.53
	Biological Yield	-0.52	-0.03	1.03	0.334	0.11		0.93*
April 15th	Plant Height	-0.49		0.00	-0.04	0.21	0.16	-0.16
	Panicle Length	0.15	-0.01		0.01	-0.21	1.03**	0.97**
	Seeds Number	0.05	0.37	0.02		-0.25	-0.04	0.16
	1000 Seed Weight	-0.36	0.29	0.09	0.04		0.56	0.62
	Biological Yield	1.06	-0.07	0.14	-0.00	-0.19		0.94**
May 15th	Plant Height	0.03		-0.10	0.02	-0.00	-0.21	-0.33
	Panicle Length	0.39	0.01		-0.00	0.03	0.53*	0.95**
	Seeds Number	0.02	-0.03	-0.08		0.00	-0.25	-0.33
	1000 Seed Weight	0.05	0.00	0.25	0.00		0.24	0.55
	Biological Yield	0.61	0.01	0.34	-0.01	0.02		0.97**

PH: plant height, PL: panicle length, SN: seed numbers, TSW: thousand seed weight, BY: biological yield

The study of the direct and indirect effects of traits on seed yield in two planting densities showed that the most direct effect on seed yield belonged to thousand-seed weight. The high correlation between seed yield and biological yield in planting density of 40 plant/m^2 was due to its indirect effects through other studied traits, especially thousand-seed weight. In the planting density of 60 plant/m^2, however, the direct effect of biological yield was negative but had a high indirect effect through panicle length. It seems that increased biological yield at different planting densities and dates plays a vital role in increasing yield (Table 10).

Phenological stages

The results showed that the Q_{29} genotype had a more extended phenological stage than those of the other two cultivars. Also, the ripening period of quinoa plants with the March 15th sowing date was longer than those of the other two sowing dates. The differences in the ripening period can be attributed to changes in environmental conditions including daily temperature and length of day (Table 11).

The main concern in spring quinoa cultivation is the possibility of synchronicity in the high-temperature with pollination stage, which can have a seriously destructive effect and significantly reduce seed formation. The faster this stage (flowering and pollination) followed by less possibility of synchronicity with high temperatures, the higher the yield components including the number of seeds and 1000-seed weight. Therefore, early spring cultivars are generally more suitable for quinoa cultivation.

Table 10. Path coefficient analysis of planting densities showing direct and indirect effects of traits on seed yield in quinoa

Plant density	Plant Traits	Direct effect	Indirect effects					
			PH	PL	SN	TSW	BY	r
40 plants m^{-2}	Plant Height	-0.01		0.07	0.15	0.04	0.08	0.33
	Panicle Length	0.22	0.00		0.18^{*}	0.37^{**}	0.22^{**}	0.99^{**}
	Seeds Number	0.25	0.00	0.16		0.16	0.16^{*}	0.73^{*}
	1000 Seed Weight	0.41	0.00	0.20	0.10		0.20^{**}	0.91^{**}
	Biological Yield	0.23	0.00	0.22	0.18	0.36		0.99^{**}
60 plants m^{-2}	Plant Height	0.01		0.27	-0.01^{*}	-0.01	-0.06	0.20
	Panicle Length	1.20	0.00		0.00	0.07^{**}	-0.27^{**}	1.00
	Seeds Number	0.01	-0.01	0.01		0.02	0.00	0.02
	1000 Seed Weight	0.08	0.00	1.07	0.00		-0.25	0.90^{**}
	Biological Yield	-0.27	0.00	1.19	0.00	0.07		0.99

PH: plant height, PL: panicle length, SN: seed numbers, TSW: thousand seed weight, BY: biological yield

Table 11. Two-year mean phenological stages of quinoa genotypes (day) at different sowing dates and plant densities in the Kermanshah region, according to the extended BBCH scale (Sosa-Zuniga et al., 2017).

		Emergence of cotyledons through soil	Nine pair of leaves visible	Inflorescence emergence	Ripening period
Sowing date	March 15th	7.07	30.22	41.61	154.66
	April 15th	6.06	27.27	35.66	144.11
	May 15th	5.6	25.44	22.27	139.11
Genotype	Titicaca	5.61	26.94	3466	138.7
	Redcarin	6.35	27.77	36.55	147.55
	Q29	6.77	29.22	38.33	151.33
Density	40 plant/m^2	6.62	28.4	37.81	147.
	60 plant/m^2	5.86	26.88	35.22	144.29

CONCLUSIONS

The results of this experiment showed that genotypes and planting dates are the most determining factors affecting quinoa growth, development, and seed yield compared with planting densities. In the current study, the most optimal agronomic technique was obtained by planting Titicaca genotype on April 15th, 2019, and/or May 15th, 2020, with a planting density of 60 plants m^{-2} in Kermanshah which is recommended for the area and/or areas with similar climatic conditions to achieve the highest seed yield. Further research is needed to understand better the phonological, morphological, and agronomical responses of quinoa genotypes (Titicaca, Q29, and Red Carina) to different sowing dates and planting densities higher than 60 plants m^{-2}.

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تأثیر تاریخ کاشت و تراکم بوته بر عملکرد دانه و اجزای عملکرد ژنوتیپ‌های کینوا (*Chenopodium quinoa*)

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همبستگی

چکیده - کینوا (*Chenopodium quinoa*) به دلیل فواید تغذیه ای و سلامتی و سازگاری با محیط های مختلف مورد توجه ویژه‌ای در سراسر جهان قرار گرفته است. با وجود تحقیقات انجام شده در مورد کشت کینوا، تعیین تاریخ و تراکم مناسب کاشت آن برای ژنوتیپ‌ها و مناطق مختلف نیاز به بررسی و مطالعه دارد. از اینرو، هدف اصلی مطالعه حاضر تعیین اثرات تاریخ کاشت و تراکم کاشت بر عملکرد بذر کینوا در شرایط اقلیمی کرمانشاه بود. برای این منظور اثر تاریخ کاشت (۲۵ اسفند، ۲۵ فروردین و ۲۵ اردیبهشت)، تراکم بوته (۴۰ و ۶۰ بوته در متر مربع) و ژنوتیپ (Titicaca، Q29 و Red Carina) بر عملکرد و اجزای عملکرد گیاه کینوا، در آزمایشی به صورت اسپلیت پلات فاکتوریل در قالب بلوک‌های کامل تصادفی با سه تکرار به مدت دو سال (۱۳۹۷-۱۳۹۸ و ۱۳۹۸-۱۳۹۹) در مزرعه تحقیقاتی دانشگاه رازی کرمانشاه انجام شد. تاریخ کاشت به عنوان کرت اصلی، تراکم بوته و ژنوتیپ‌ها به عنوان کرت‌های فرعی بودند. نتایج نشان داد که بیشترین عملکرد دانه (۲۱۷۹/۷۲ و ۲۲۶۷/۳۹ کیلوگرم در هکتار) به ترتیب در ۲۵ فروردین ۱۳۹۸ و ۲۵ اردیبهشت ۱۳۹۹ به دست آمد. تاریخ کاشت ۲۵ فروردین و ۲۵ اردیبهشت با تراکم بوته ۶۰ بوته در متر مربع و ژنوتیپ Titicaca بیشترین عملکرد دانه را برای کاشت کینوا در شرایط اقلیمی کرمانشاه داشتند. همچنان نتایج نشان داد که صفات طول خوشه و عملکرد بیولوژیکی همبستگی مثبت و معنی‌داری با عملکرد دانه در تمام تاریخ‌های کاشت مورد مطالعه داشت. همبستگی مثبت و معنی‌داری بین عملکرد دانه و وزن دانه در بوته، وزن هزار دانه، عملکرد بیولوژیکی در هر دو تراکم وجود داشت. تجزیه مسیر نشان داد که طول خوشه بیشترین تاثیر مستقیم مثبت را بر عملکرد دانه و وزن هزار دانه در تاریخ کاشت ۲۵ اسفند ماه داشت، درحالی که عملکرد بیولوژیک و طول خوشه بیشترین اثر مستقیم مثبت را بر عملکرد دانه به ترتیب در تاریخ کاشت ۲۵ فروردین و ۲۵ اردیبهشت داشتند. نتایج مطالعه حاضر نشان داد که رقم و تاریخ کاشت در مقایسه با تراکم بوته تعیین کننده ترین عوامل موثر بر رشد، نمو و عملکرد دانه گیاه کینوا هستند.