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Research Article

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Effects of different mixtures of maize and quinoa intercropping on grain yield and fatty acid composition of oil under water reduction

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Abstract

The objective of this study was to ascertain the impact of drought on quinoa (*Chenopodium quinoa*) and maize (*Zea mays* L.) grown in intercropping at varying mixing rates, which represents a model of sustainable agricultural food production under the Mediterranean climate. The experiment included plots with five different crop combinations (25% quinoa - 75% maize, 50% quinoa - 50% maize, and 75% quinoa - 25% maize) as well as monoculture (100% quinoa and 100% maize). To ensure drought stress, plots with half the water holding capacity of the soil (W2) were used in addition to the full water holding capacity of the soil (W1). Drought stress caused dramatic decreases in the seed yield of both crops. The addition of a low rate of quinoa (25%) to the cultivation plot did not have a significantly (less than 10%) negative effect on the maize yield, despite the reduction in the number of maize plants. Similarly, growing a low rate of maize (25%) between quinoa rows increased quinoa yield under both irrigation conditions ($P < 0.01$). The Water Use Efficiency (WUE) and Irrigation Water Use Efficiency (IWUE) calculated from the 25% quinoa - 75% maize was very close to those of the 100% maize in the W1 condition. Besides, the values under W2 exceeded those of the maize monoculture. Furthermore, all mixed plots had greater land equivalence rate (LER) values (>1) than those grown alone. Drought stress significantly affected the composition of oil, increasing palmitic acid and decreasing oleic, linoleic, and linolenic acid. The findings demonstrate that under conditions of drought stress, intercropping of quinoa and maize can partially tolerate reductions in both the product quantity and the composition of oil. These results indicate a harmonious relationship between the plants, particularly when the mixing rates include 25% quinoa-75% maize and 75% quinoa-25% maize.

Keywords: drought; fatty acids; IWUE; LER; mixing rates; WUE; yield

Introduction

Intercropping, also known as mixed culture, entails cultivating multiple crops simultaneously in a shared space and timeframe, as opposed to polyculture growing different crops in the same area at various dates

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throughout the year or over multiple years (Kumar *et al.*, 2021). It is one of the preferred methods for a sustainable farming system dating back to ancient times in small-scale agricultural enterprises (Dai *et al.*, 2019). It is a way of increasing the productivity of a given area of land and gaining an advantage in terms of yield (Jensen *et al.*, 2020). In addition to the distribution of the labor force (spreading it over different periods during the year), the system creates different income sources for the enterprises as a result of different production materials. It reduces the need for weeding and the use of insecticides, herbicides, or fungicides (Redlich *et al.*, 2018) because of the suppression of disease (Chang *et al.*, 2020), pests or weed species (Lopes *et al.*, 2016) with increases in the diversity of crops (Chi *et al.*, 2021). The system also contributes to an increase in water use efficiency through the crops with different root structures (Rahman *et al.*, 2016) thanks to the use of soil layers at different depths. In this way, it helps to protect the diminishing water sheds of the agroecosystem in many agricultural regions during the climate change period (Qian *et al.*, 2018). For this reason, the system prioritizes environmentalism as well as profitability.

Maize (*Zea mays* L.) production quadrupled in the 2000s (from 2000 to 2020), and more than one billion tons (1 billion 210 million tons) were produced on approximately 206 million ha in 2021 (FAO, 2021). Although maize production has increased, its stock in the world has decreased daily due to the wide range of usage areas (food and feed industry, bioenergy, starch-based sugar, etc.) (Hamulczuk and Makarchuk, 2020). Therefore, in numerous regions with favorable climate and soil conditions, the cultivation of multiple agricultural production systems (Isbell *et al.*, 2017) containing a variety of crops (polyculture or intercropping) is being explored alongside single-crop (monoculture) farming.

Creating an intercropping system requires proper planning and knowledge of the crops to be included. Maize has been produced together with many different crops (soybean, broad bean, peanut, sunflower, etc.) in the past (Zhang *et al.*, 2014; Jiang *et al.*, 2022; Li *et al.*, 2023), but it mostly suppressed the other crops due to its vegetative characteristics (shade effect with high height and leaf volume) (Liu *et al.*, 2017; Wang *et al.*, 2017). The question of whether maize and quinoa can be an example of intercropping for seed production has been raised recently. There have even been some studies on silage yield and growth parameters (Koca, 2021) for the crops in intercropping. However, there have been no comprehensive studies on the production or content of crop seeds. In addition to silage production, maize seeds are popular, provide a high yield of minerals, carbohydrates and energy and are an important source of food/feed for people and poultry, livestock and some other animals worldwide (Keller *et al.*, 2022). On the other hand, quinoa seed has become increasingly popular as a healthy food option, and it is rich in vitamins, antioxidants and minerals (Liu *et al.*, 2020) in addition to having a high nutritional content (Nascimento *et al.*, 2014) content. Furthermore, it is commonly acknowledged as a superfood for vegans (Felix *et al.*, 2021) and people who are gluten and lactose intolerant, as it is gluten free and meets the need for calcium (Moss and McSweeney, 2021).

Given this background, our study aimed to determine the effect of different crop mixture rates on the grain yield and oil rate, as well as fatty acid distribution of oil in quinoa and maize seeds, under both full irrigation (100%) and restricted irrigation (50%) conditions. Additionally, water use efficiency (WUE) and Irrigation Water Use Efficiency (IWUE) and land equivalence rate (LER) values were calculated to assist in the interpretation of the results. This research sought to evaluate the compatibility of these crops, their responses to water reduction, and the stress-reducing potential of various mixture rates in terms of seed production and quality in an intercropping system in accordance with the prevailing Mediterranean climatic conditions.

Materials and Methods

Crop material and experiment establishment

The study was conducted in the field of Adnan Menderes University Faculty of Agriculture Application and Research Farm (27° 51'E, 37° 51'N, altitude 50 m) in Aydın Province in western Turkey under the conditions of summer main crops in 2020 and 2021. The SY Fuerza hybrid maize is a product of Syngenta Co., whereas the Valiente quinoa variety was obtained from the Quinoa Growers Association in the locality. The SY Fuerza hybrid maize variety used in the experiment is known for its high yield potential and drought tolerance, making it suitable for Mediterranean climates. The Valiente quinoa variety is a mid-season genotype characterized by its adaptability to semi-arid environments, and it exhibits a compact plant structure and strong resistance to lodging. Quinoa seeds generally exhibit a high germination capacity, often exceeding 90% under favorable conditions. In this study, certified Valiente quinoa seeds with a germination rate above 92% were used, ensuring uniform plant emergence and consistent crop density across plots. The study materials have comparable vegetation periods of around 140 days, making them appropriate for summer growing in the Mediterranean climatic region (Lavini *et al.*, 2014). The experiment was set up in a randomized block design based on a split-plot design with three replicates. The main plots consisted of two irrigation treatments, full (100% water dose) and deficit dose (50% water dose) according to the soil water holding capacity using drip irrigation, and the subplots were determined as the crop mixtures. "100% maize" and "100% quinoa" (monoculture) were made by growing this crop (maize or quinoa) in all 4 rows of the plots. The planting strategy of "25% quinoa - 75% maize" involved planting a single row of quinoa in the center of the plot, with the remaining three rows dedicated to maize. The reverse was true for the "75% quinoa - 25% maize". The "50% quinoa - 50% maize" plot was also created by growing half maize and half quinoa. A schematic diagram outlining the field trial layout for monoculture and intercropping plots, along with corresponding pictures, were given in Figure 1. The plot size was determined to be 33.6 m^2 (row length of 12 m). Sowing was carried out on 11/05/2020 and 02/05/2021 using a pneumatic seeder, with the planting rows spaced 70 cm apart and the individual plants within each row spaced 16.8 cm apart. The emergency dates were set as 20/05/2020 and 15/05/2021. During the experimental period, phenological observations such as flowering time, silking in maize, and heading in quinoa were recorded. These indicators were used to schedule irrigation and nutrient applications. The maize variety reached tasseling at around 60 days after sowing, while quinoa reached flowering at around 65 days. Both crops reached physiological maturity between 115-125 days depending on water availability.

The average of temperatures and precipitation values of Aydın in the 2020 and 2021 summer seasons and the averages for long years were given in Figure 2. Monthly precipitation amounts from April to September in 2020 (especially in April, May and June) were above the long-year averages. Accordingly, the first year was quite hot and rainy, especially during the vegetative period of the crops. However, the second year of the study (2021) was slightly different in terms of both temperature and especially precipitation. There was a severe drought from the pre-planting and seedling stage to the end of the vegetative period in 2021.

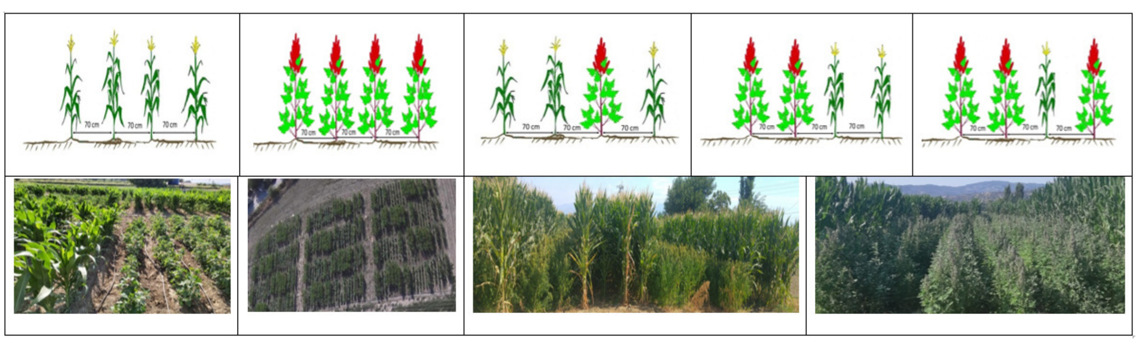

Figure 1. Demonstration of field trial design for monoculture and intercropping plots (respectively) and some visuals of the trial field

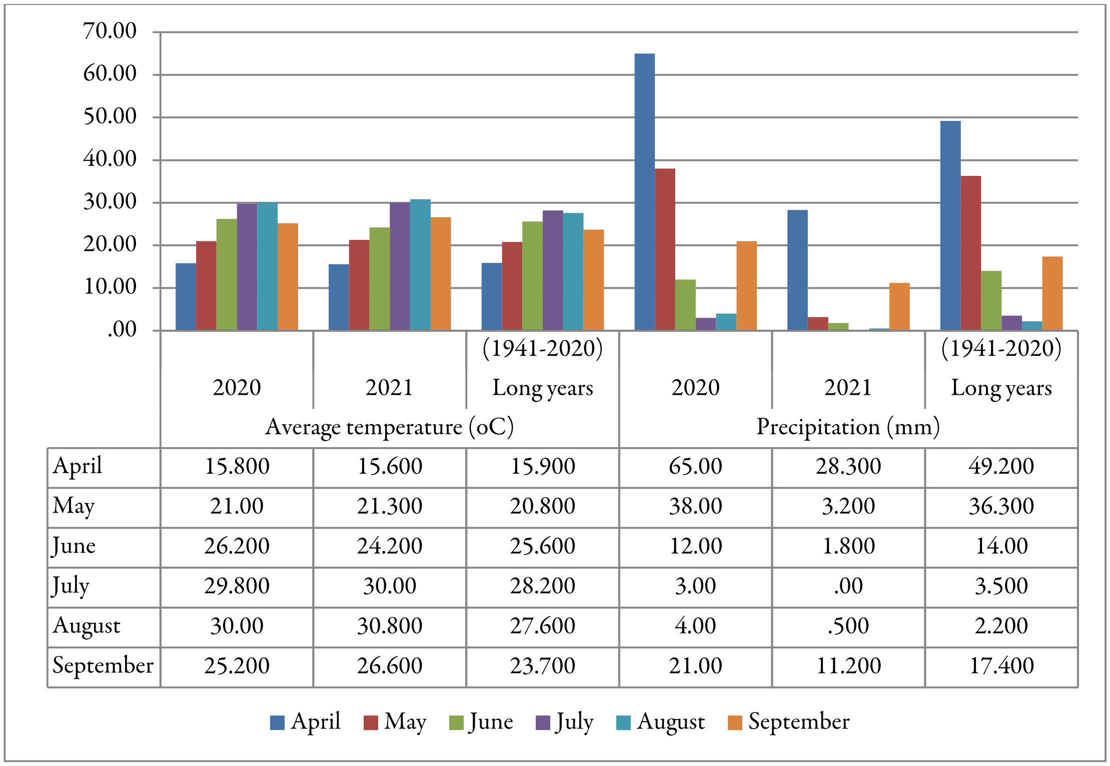

Figure 2. Monthly average of temperature and total precipitation values for Aydın province

Soil structure

The field capacity (FC) values of the soils in the experimental area varied between 20.3% and 23.1%, and the wilting point (WP) values varied between 7.2% and 10.1%. Values between 1.35-1.52 g cm^{-3} were determined for each layer that differed in terms of volume weight. In the texture analysis report, the soils had a sandy-loamy (Table 1). Table 2 showed that the soil of the experimental field was defined as alkaline, salt-free, highly calcareous, and low in phosphorus and potassium. Moreover, the amount of organic matter in the soil (1.05%) was also low.

Calculation of applied irrigation water

Irrigation issues were created as the reapplication of 100% (W1) and 50% (W2) of the water decreased at the effective root depth (90 cm). Soil moisture levels were determined by the gravimetric method (Whalley, 1993). The irrigation in the W1 treatment started when approximately 50% of the usable water holding capacity in the 90 cm soil profile was consumed. The amount of irrigation water given to the other treatment was determined based on the irrigation practices in the W1 treatment.

Table 1. Physical properties of the soil (average of the years)

Profile Depth (cm)	Structure Distribution (%)			Volume Weight (g cm^{-3})	Field Capacity		Fading Point		Usable Water Retention Capacity	
	Sand	Clay	Silt		(%)	(mm)	(%)	(mm)	(%)	(mm)
0-30	58.40	13.60	28.00	1.35	23.1	111.5	10.1	40.9	13.0	52.6
30-60	56.40	13.60	30.00	1.45	22.9	99.6	9.4	40.8	13.5	58.8
60-90	68.20	13.60	19.20	1.52	18.4	83.9	7.3	33.2	11.1	50.6
90-120	49.70	17.50	32.0	1.50	20.3	91.3	7.2	32.3	13.1	59.0

Table 2. Chemical properties of the soil

Layer Depth (cm)	pH	Total Salt (%)	EC (ds/m)	$CaCO_3$ (%)	Usable Nutritional Materials (kg ha^{-1})		Organic Matter (%)
					P_2O_5	K_2O	
0-40	8.0	0.015	0.54	11.40	39.0	185.0	1.05

The amount of irrigation water to be applied to W1 subjects for each recurrence in drip irrigation plots was determined with the help of the following equation (Heerman, 1985).

$$I= ((FC-\Delta W)/100) \times \gamma t \times D \quad (1)$$

$$V = I \times A \times P \quad (2)$$

I: The amount of irrigation water given in each irrigation (mm), FC: Moisture retained at field capacity (% Pw), ΔW: Current humidity (% Pw), ɣt: The volume weight of the soil (g cm^{-3}) and D: Effective root depth (mm) V: The volume of irrigation water to be applied in each irrigation (L), A: Parcel area (m^2) and P: Wetting area percentage (%)

Crop water consumption

The water budget method developed by Kanber (1993) was used to determine seasonal water consumption. Since there was no ground water in the experimental area, it was assumed that there was no water inflow to the root zone by capillary action, and Cp and Rf values were neglected because surface flow was not allowed.

$$ET = I + P + Cp - Dp \pm Rf \pm \Delta S \quad (3)$$

ET: Crop water consumption (mm), I: Amount of irrigation water applied (mm), P: Amount of precipitation falling during the trial (mm), Cp: Amount of water entering the root zone with capillary rise (mm), Dp: Occurs after irrigation and precipitation infiltration losses (mm), Rf: The amount of surface flow entering or leaving the trial plots (mm), ΔS: The change in soil moisture content (mm) for the measured period.

Irrigation treatments consisting of different water levels (full and low) were determined as the irrigation water needed for the root zone soil water to rise to field capacity (100%) and half of field capacity (50%).

Water use efficiencies (WUE and IWUE)

The water use efficiency (WUE) was calculated by dividing the grain yield of the crops in the mixed plots by the crop water consumption for each subject. Moreover, to obtain the irrigation water utilization efficiency (IWUE) values, the grain yields obtained from the crops in the mixed plots under the influence of different irrigation water applied to the trial subjects were examined (Howell *et al.*, 1990). The calculations (WUE and IWUE) were based on the averaging of replicates.

$$WUE = Y/ET \ (\text{kg m}^{-3}) \quad (4)$$
$$IWUE = Y/I \ (\text{kg m}^{-3}) \quad (5)$$

Y = Grain yield (kg ha^{-1}), ET = Seasonal water use (mm), I = applied irrigation water (mm)

Fertilization and other agricultural practices

All field works of the study were executed following accepted agricultural practices for future practical application under farming conditions in accordance with conventional agriculture. The fertilization program was prepared in three stages, accounting for the soil analysis results and the needs of maize. Initially, 100 kg of pure nitrogen, phosphorus and potassium (15-15-15 composites) were applied per hectare before planting. Then, the second round of fertilizer (60 kg ha^{-1} pure N in the form of ammonium sulfate) was applied when the maize was in the 6-8 leaf stage, and the last round of fertilizer was applied with drip irrigation (60 kg ha^{-1} pure N in the form of ammonium nitrate) while tassels were being removed from the maize crop. No herbicide was applied. Instead, machine hoeing was carried out 2 times (3-5 leaf stage and 6-8 leaf stage) between the crop rows, in addition to two times hand hoeing for intra-row weed control during the seedling stage.

Measurements

Grain yield and oil rate

The middle two rows from each plot consisting of 4 rows were harvested by hand. The harvesting process was carried out separately over a distance of ten meters, from the beginning to the end, following the removal of edge effects. And the maize and quinoa seeds collected from the different mixed plots were taken to the storeroom. Subsequently, grain yield values (kg ha^{-1}) were computed based on plot size and mixture rates. The oil rate parameter of the obtained seeds was measured using the NIRSFT (Bruker MPA) instrument, as per the methods described by Fassio *et al.* (2009) and Ferreira *et al.* (2015).

The analyses of fatty acids

Fatty acid methyl esters were prepared according to the International Union of Pure and Applied Chemistry (IUPAC) method and analyzed by gas chromatography. The 0.4 g of sample was dissolved in 4 mL isooctane and then mixed with 0.2 mL of 2 N methanolic KOH. The solution was mixed and stored in the dark for 6 min. 0.45 mL of 1 N HCl solution was incorporated to the solution with a few methyl orange. Chromatographic separation was performed with a DB-23 silica column (n60 m x 0.25 mm inner diameter x 0.25 µm film thickness). Column, injector and detector temperatures were 195 °C, 230 °C and 240 °C, respectively. The carrier gas was nitrogen, and the flow rate was 1 ml/min. The results are given as % methyl esters (IUPAC, 1991).

Land equivalence rate (LER)

Intercropping is a farming practice that involves growing two or more crops together in the same field. The land equivalent rate (LER) is a measure used to assess the productivity of intercropping systems (Metwally *et al.*, 2019). There is increased light interception and improved utilization of moisture and nutrients in intercropping systems, resulting in higher crop production compared with pure cropping (Jiang *et al.*, 2022). LER is calculated as the rate of the yield of a sole crop to the yield of the same crop when grown in an intercropping system, added to the yield of the intercrop divided by the yield of the same intercrop when grown alone. LER was determined with the help of the following modified equation:

$$LER = GYmi/GYma + GYqi/GYqa \quad (6)$$

GYma = grain yield of maize alone; GYqa = grain yield of quinoa alone; GYmi = grain yield of maize in intercrop; GYqi = grain yield of quinoa in intercrop

Statistical analysis

The crops' data was analyzed separately using the TARIST statistical package (Acikgoz *et al.*, 2004), and an analysis of variance (ANOVA) was performed. The LSD test was used for grouping, enabling the evaluation of the differences that arose.

Results and Discussion

Soil water content

In the experiment, the differences in the amount of moisture found at the effective root depth of 90 cm during the irrigation season in each plot were shown separately in Figure 3 for each irrigation treatment (W1 and W2). In addition, the values of soil water content in the irrigated plots showed different values between field capacity and 50% moisture reduction values. Irrigation should be scheduled when the available soil water has depleted by a maximum of 45% to attain the highest grain yield possible of growth for maize cultivated in subtropical regions under conditions of water scarcity (Panda *et al.*, 2004).

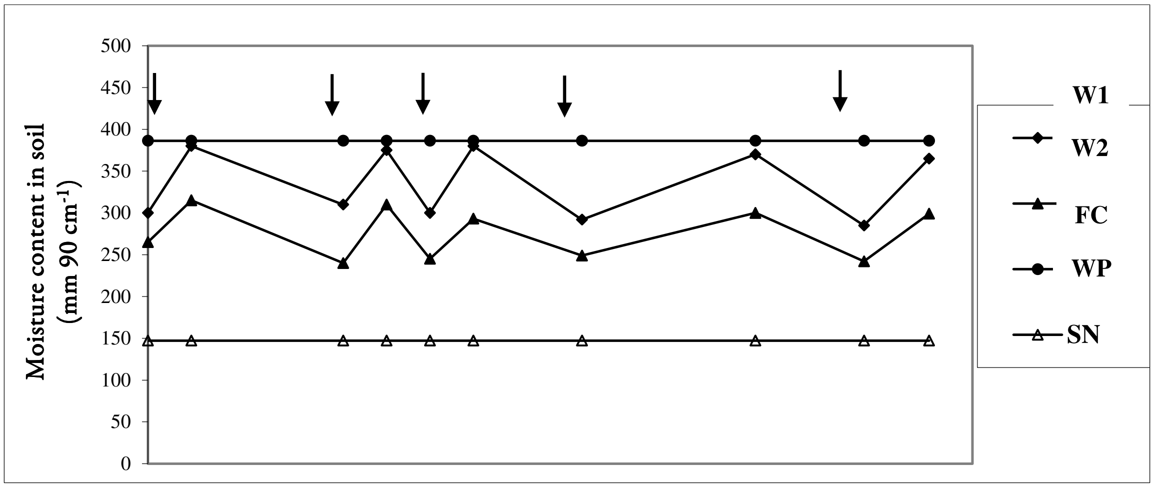

Figure 3. Change of soil moisture during the season (average of 2020 and 2021) (W1: 100%, W2: 50%, FC: Field Capacity, WP: Wilting Point)

Irrigation water quantity

The irrigation water amount values obtained from each subject during the development period were given in Table 3. The first watering was applied to the trial plots when 40% of the useful water was consumed, and this period was determined as 11 June 2020. The last water was applied on 17 August, and a total of 8 irrigation applications were made throughout the season. In 2021, the first watering was applied on 30 May, the last water was applied on 21 August, and 10 irrigations were made during the season. In the initial year of the research, the highest water quantity was measured in the W1 treatment, with a value of 712.8 mm, whereas the smallest level of consumption was observed in 2021's W2 treatment, with a value of 315.9 mm.

Water use efficiencies (WUE and IWUE)

To facilitate the evaluation of this, the average data with maize and quinoa growing alone were colored blue and red, and the mixture was colored according to the proportions of the crops in the mixture. WUE and IWUE were collected because there were two different crops in the same area (Table 3).

Average of WUE and IWUE values grown in mixed under W1 and W2 WUE and IWUE showed differences between years (Table 3). In the first year of the study, the mean WUE and IWUE were 1.61 and 1.68 under 100% irrigation conditions. In the second year, the values were 1.32 and 1.33, respectively. The significant decrease in these calculated values may be due to the difference in rainfall between the years. The sharp reduction in rainfall that occurred before planting in the second year may have reduced the water reserve in the soil. In addition, high temperatures and a lack of rainfall were observed during the seedling period (Figure 2). The situation indicated that the soil water reserve was very low at the beginning. This may have caused stress to the crops during the seedling period (before irrigation) in the second year. It was therefore expected that crops would be adversely affected despite irrigation. The results obtained from the 50% irrigation condition also supported this.

Table 3. Average of WUE and IWUE values grown in mixed under W1 and W2

Water dose	Irrigation water quantity (mm)		Crop water consumption (mm)		Mixed rate	WUE (kg m^{-3})		Total		IWUE (kg m^{-3})		Total		LER	
	2020	2021	2020	2021		2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
100% (W1)	631.5	712.8	658.3	718.1	%100 Q	0.28	0.22	0.28	0.22	0.29	0.23	0.29	0.23	-	-
					%75Q - %25M	0.31	0.27	1.19	0.95	0.33	0.27	1.25	0.95	1.48	1.51
						0.88	0.68			0.92	0.68				
					%50Q - %50M	0.13	0.15	1.68	1.45	0.14	0.16	1.75	1.47	1.09	1.34
						1.55	1.30			1.61	1.31				
					%25Q - %75M	0.10	0.12	2.38	1.97	0.10	0.12	2.48	1.98	1.26	1.45
						2.28	1.85			2.38	1.86				
					%100M	2.52	2.02	2.52	2.02	2.62	2.03	2.62	2.03	-	-
50% (W2)	315.9	356.6	342.7	361.9	%100 Q	0.24	0.27	0.24	0.27	0.26	0.27	0.26	0.27	-	-
					%75Q - %25M	0.37	0.29	1.65	1.42	0.40	0.30	1.78	1.44	1.75	1.77
						1.28	1.13			1.38	1.14				
					%50Q - %50M	0.18	0.26	1.67	1.84	0.19	0.26	1.81	1.86	1.32	1.42
						1.49	1.58			1.62	1.60				
					%25Q - %75M	0.12	0.11	2.23	2.43	0.13	0.19	2.42	2.54	1.50	1.67
						2.11	2.32			2.29	2.35				
					%100M	2.28	2.33	2.28	2.33	2.48	2.37	2.48	2.37	-	-

Q: quinoa and M: maize

Regarding crops, maize (100%) had the highest WUE and IWUE under W1 (2.27 and 2.33, respectively) and W2 (2.31 and 2.43, respectively) applications, based on two-year averages. On the other hand, the average values for quinoa were quite low under W1 (0.25 and 0.26, respectively) and W2 (0.26 and 0.27, respectively). Only different water doses (W1 and W2) did not have a serious effect on the WUE and IWUE, but the crop mixtures did. The total WUE and IWUE varied according to the mixing rates of crops. The total values increased even when a small amount of maize (25% maize) was added to the mixture under both irrigation treatments (W1 and W2). It was also observed that the 100% maize and the 25% quinoa - 75% maize had very similar total WUE and IWUE in both years under the W1 treatment. In particular, the WUE and IWUE calculated for the 25% quinoa - 75% maize (2.43 and 2.54, respectively) exceeded those of the maize grown alone (2.33 and 2.37, respectively) in 2021 under W2.

Due to its C4 plant type, maize is acknowledged for its high water use efficiency. Although quinoa, a C3 plant, has low values of IWUE and WUE, it is also recognized for thriving in arid conditions, which enhances its water conservation capabilities. Additionally, the positive effects of the crop may differ across various mixtures (Vahidi *et al.*, 2021; Tesfuhuney *et al.*, 2023). Maize and quinoa can improve the structure of different soil depths and capable of nutrient uptake through soil layers (Yong *et al.*, 2015) due to different rooting patterns (Rahman *et al.* 2016). We can say that the two crops have the potential to be mutually beneficial. Intercropping has many benefits for crops. In particular, it reduces evaporation and improves both water and nutrient use efficiency by sharing resources between morphologically different crops.

Grain yield

Analysis of variance on the study's data reveals a significant difference between years in grain yield and quality (Table 4). Thus, we presented the data obtained by evaluating individual years (Table 5), as well as the annual average mean squares and LSD 0.05 values.

The grain yields under W1 were determined to be 1352 kg ha^{-1} and 1371 kg ha^{-1} for quinoa and 11892 kg ha^{-1} and 10446 kg ha^{-1} for maize in the first and second years, respectively. The grain yield deceased to 772 kg ha^{-1} and 915 kg ha^{-1} in quinoa and 6135 kg ha^{-1} and 6658 kg ha^{-1} in maize under W2. The restriction of water significantly ($P < 0.01$) reduced the grain yield of the crops. When calculated with two-year averages, the reduction in the grain yield of quinoa was approximately 38%, while the reduction in maize was 42%. Therefore, the adverse effect of restricted water was greater in maize than in quinoa.

Table 4. Variance analysis results

Variation source	Grain yield		Oil	
	Maize	Quinoa	Maize	Quinoa
Water dose (WD)	2747217.0**	31917.2**	0.6**	0.5**
Error 1	56.1	29.3	0.0	0.0
Mixing rate (MR)	1279615.3**	21414.5**	0.2*	1.0**
Year (Y)	24396.9**	740.5**	3.4**	3.7**
WD*MR	230954.5**	3795.1**	0.1ns	1.7**
WD*Y	120051.0**	486.6**	0.0ns	0.3**
MR*Y	2645.7ns	1369.7**	0.1ns	0.3**
WD*MR*Y	6876.6ns	300.4**	0.1ns	0.3**
Common Error	2392.2	13.2	0.0	0.0

*: $P < 0.05$, **: $P < 0.01$ significant, ns: no significant, (WD*MR): (Water dose*Mixing rate)

An approximately 10% difference in maize grain yield was found between the 100% maize and the 25% quinoa - 75% maize under W1 condition. However, water constraints negatively affected the maize yield. As a result of our study, just adding a small amount of quinoa (25%) into the cultivation under 50% irrigation conditions did not adversely affect the maize yield too much. The maize grain yields obtained from 25% quinoa - 75% maize for two years (7223 kg ha^{-1} and 8392 kg ha^{-1}, respectively) were statistically similar to the yield of 100% maize.

The maximum grain yield of quinoa occurred in the 75% quinoa - 25% maize in both years (2071 kg ha^{-1} and 1915 kg ha^{-1}, respectively) under W1. Similarly, the plots had the highest quinoa grain yield under W2 conditions in both years (1255 kg ha^{-1} and 1074 kg ha^{-1}, respectively). The quinoa grain yield increased with the addition of a small amount of maize (25%) into the cultivation plot under both W1 and W2 treatments. Maize has been grown in intercropping studies with plants of varying characteristics in the past (Han *et al*, 2023). There could be reasons for the increase in the production of the mixed plots. Firstly, the root structures of the crops are different. Quinoa has an extensive ramified and deeper root system (Kakabouki *et al.*, 2019). On the other hand, maize possesses a root system that could be described as a plant suited for surface-level growth and can readily adjust to variations in its surroundings (Hochholdinger, 2009). Second, while maize has a typical grassy leaf structure (lanceolate), quinoa has a segmented, broad leaf structure. To withstand drought stress, quinoa adapt by producing a thick and waxy layer on their leaf cuticle, which contains hygroscopic papillae to reduce transpiration (Jacobsen *et al.*, 1997). In maize, the lanceolate leaf structure is optimized to maximize solar exposure (Feng *et al.*, 2019) while minimizing moisture loss (Anjum *et al.*, 2016). The different leaf structures may also have made these two crops complementary. Finally, restricted stress during crop growth between crops with intercropping can sometimes have effects that increase crop growth. This situation can be explained by positive interactions, such as facilitation and complementarity, associated with competition for crop resources in the intercropping. The presence of two different crops in the same area (in the same plot) creates stress on both of them. This was also the case in the "25% quinoa - 75% maize" and "75% quinoa - 25% maize" plots in our study. As a result of the results, it can be said that intercropping is more beneficial considering the total amount of product (quinoa and maize seeds) obtained from the plots than monoculture.

Table 5. Grain yield and oil rate of quinoa and maize grown in mixed under W1 and W2

Water dose	Mixing rate	Quinoa				Maize			
		Oil (%)		Grain yield (kgha^{-1})		Oil (%)		Grain yield (kgha^{-1})	
		2020	2021	2020	2021	2020	2021	2020	2021
100% (W1)	100%Q	4.3	3.9	1840	1600	-	-	-	-
	100%M	-	-	-	-	1.7	2.2	16544	14471
	75%Q-25%M	4.7	4.1	2071	1915	1.7	2.0	5814	4686
	50%Q-50%M	4.4	3.8	860	1111	1.8	2.5	10187	9342
	25%Q-75%M	5.8	4.5	636	851	1.9	2.4	15022	13283
Average		**4.80**	**4.08**	**1352**	**1371**	**1.78**	**2.28**	**11892**	**10446**
50% (W2)	100%Q	5.7	4.9	810	991	-	-	-	-
	100%M	-	-	-	-	1.9	2.7	7819	8431
	75%Q-25%M	4.0	4.4	1255	1074	1.8	2.7	4375	4078
	50%Q-50%M	4.0	4.1	616	931	2.1	2.5	5122	5731
	25%Q-75%M	4.8	4.3	408	662	2.0	2.2	7223	8392
Average		**4.63**	**4.43**	**772**	**915**	**1.95**	**2.53**	**6135**	**6658**
Mean square values		**1.7****	**0.4****	**24742.0****	**16212.0****	**0.0^{ns}**	**0.2****	**1560464.0****	**817847.0****
LSD 0.05 (WD*MR)		**0.13**	**0.16**	**63.0**	**68.7**	-	**0.25**	**1205.0**	**512.0**

*:P<0.05, **:P<0.01 significant, ns: no signif. (WD*MR): Water dose*Mixing rate, Q: quinoa, M: maize

Oil content

Oil rates of quinoa and maize seeds values were determined in Table 5, together with the annual mean squares and LSD 0.05 values. Fatty acid composition of oil of quinoa and maize seeds were also evaluated, as shown in Figure 4 the corresponding LSD 0.05 values were included.

The maximum oil content of quinoa seed was obtained from 25% quinoa - 75% maize in both years under W1 condition (5.8% and 4.5%, respectively). For maize seeds, the maximum values were coming from 25% quinoa - 75% maize (1.9%) in the first year and the 50% quinoa - 50% maize (2.5%) in the second year under the W1. Only the oil content increased with full irrigation in the two different mixtures also increased slightly with restricted irrigation. Moreover, it can be said that quinoa seeds had higher oil content under both irrigation in the first year compared to the second year, while maize showed opposite results. In conclusion, mixed planting improves the oil rate of maize seeds without affecting the healthy status of quinoa.

There was a noticeable correlation between grain yield and oil content across mixtures. For instance, under full irrigation (W1), the 100% maize plots produced the highest grain yield (16544 kg ha^{-1} in 2020), while the 25% quinoa –75% maize mixture achieved a slightly lower yield (15022 kg ha^{-1}) but showed an increased oil content in quinoa seeds (5.8% vs 4.3% in the pure quinoa plot). Similarly, under water stress (W2), the 25% quinoa –75% maize plot maintained a high maize yield (8392 kg ha^{-1} in 2021), close to the 100% maize yield (8431 kg ha^{-1}), while quinoa oil content remained relatively higher (4.3% vs 3.9%). These findings suggest that optimized intercropping ratios, particularly 25% quinoa –75% maize, can maintain grain yield while improving oil quality — thus enhancing both productivity and nutritional value under varying water regimes.

In addition to human consumption, maize has long been used as animal feed. With the higher oil contents obtained from the study, it was thought that the quinoa seed could be used in animal feed in addition to its importance for humans. Thus, the increase in product obtained by intercropping can fill an important raw material gap in both the food and feed sectors. Concerns raised about food and feed safety have been emphasized (Ustundag *et al.*, 2016). Thus, the blends resulting from this study can be considered a new alternative for improving product quality.

Figure 4. Fatty acids composition (%) in mixed grown under W1 and W2

100% W sec. Y.: applied 100% water in second year of the experiment, 100% W first Y.: applied 100% water in first year of the experiment, 50% W sec. Y.: applied 50% water in second year of the experiment, 50% W first Y.: applied 50% water in first year of the experiment, *: P <0.05, **: P <0.01 significant, ns: no significant, (WD*MR): (Water dose*Mixing rate)

Fatty acid composition

In terms of the fatty acid composition of oil, the averages of palmitic and oleic acids in corn oil (13.36% and 23.46%, respectively) were higher than those in quinoa oil, while the averages of linoleic, linolenic and gadoleic acids in quinoa oil (64.60%, 5.97% and 0.95%, respectively) were higher. According to the results, we conclude that quinoa oil is healthier considering the levels of linoleic acid (omega-3) and linolenic acid (omega-6), which are among the essential fatty acids that should be present in a healthy diet. Furthermore, quinoa oil also contained approximately four times more gadoleic acid (0.95%), which is thought to help lower blood pressure and reduce the risk of heart disease (Galli *et al.*, 1994), than corn oil (0.13). Fatty acids are important for the body (Ryan *et al.*, 2007) because they provide a source of energy support, cell structure and function. We conclude that quinoa oil can be at least as healthy as the oil from maize or even healthier.

Reduced irrigation increased palmitic acid in both crops and both years. In addition, low irrigation also increased gadoleic acid in maize oil. On the other hand, oleic acid, linoleic acid and linolenic acid contents decreased in both crop oils under the W2 treatment. Previous studies have demonstrated that stress can alter the types of fatty acids (Feizabadi *et al.*, 2021). Drought stress can reduce the levels of unsaturated fatty acids in crop oil. On the other hand, stress can also increase the levels of saturated fatty acids (Joshan *et al.*, 2019). This is because crops produce saturated fatty acids as part of their defense against environmental stressors such as drought (Mata-Pérez *et al*, 2018). Our results were in line with expectations.

The effect of intercropping was different on maize and quinoa oil profiles. The linoleic acid content of quinoa oil increased in all mixtures under both irrigation conditions in both years. On the other hand, the other measured values fluctuated. In maize oil, linoleic acid levels measured in the first year under both irrigation conditions increased with the effect of the mixture. Moreover, the palmitic and linolenic acid levels measured in the W1 conditions in the second year also increased with the effect of the mixture. For all the other measurements, some differences and variations were observed according to the year and the mixing rate. As a result, it can be concluded that the distribution of fatty acids in the oil was affected differently by the stress caused by the mixtures, except for linoleic acid of quinoa oil.

Land equivalence rate (LER)

In the first year, LER values related to the study subjects (for different irrigation and mixes) were lower than the second-year values. The reduction in water also increased the LER values of all crop mixtures. It was also found that adding a small amount of quinoa (25%) to the mixed plots did not dramatically increase LER in either year. Therefore, it was understood that the main positive effect was obtained with the addition of maize. The maximum LER values were obtained from the 75% quinoa - 25% maize plots in the first and second years of the study under W1 (1.48 and 1.51, respectively) and W2 (1.75 and 1.77, respectively) conditions.

Intercropping is a farming practice that involves growing two or more crops together in the same field. The 25% quinoa - 75% maize and the 75% quinoa - 25% maize plots had high LER values under both irrigation conditions in both years. Our resulting LER values from other mixed-growth plots under W1 and W2 treatments were also found to be up to one (>1). LER is the sum of the relative yields of the two crops in the intercropping system divided by the sum of their relative yields when grown separately. In other words, an LER value of 1 indicates that the intercropping system is as productive as the cropping alone system, while values greater than 1 indicate that the intercropping system is more productive than cropping alone (Xu *et al.*, 2020), and values less than 1 indicate that the intercropping system is less productive than cropping alone (Meng *et al.*, 2016). Moreover, appropriate intercropping combinations increase land use efficiency compared to monocultures (Rezaei-Chiyaneh *et al.*, 2021; Li *et al.*, 2023). Our results show that all mixing rates of crops growing in the study can be positive for crops. Some intercropping systems have been reported to have LER values greater than 2, indicating a significant improvement in productivity (Mead and Willey, 1980) compared to sole cropping. However, our results did not reach the specified level.

Conclusions

Based on the data obtained, it was demonstrated that the crops possess compatible agronomic characteristics. The investigated crops were observed to have adequate height and an upright stature with no shadowing effect. Additionally, distinct root systems and leaf structures were observed, which possibly had a positive impact on each other. The study demonstrates the effectiveness of intercropping quinoa and maize under varying water conditions. Specifically, the 75% quinoa - 25% maize combination produced the highest quinoa yields under both W1 and W2 conditions in the first and second years. Meanwhile, the 25% quinoa - 75% maize combination maintained maize yields and quality comparable to 100% maize under both water treatments. The maize yields for the combination were statistically similar to the yields from pure maize plots, even under reduced irrigation conditions.

Overall, the results highlight that intercropping quinoa and maize, particularly in a 75% quinoa - 25% maize or 25% quinoa - 75% maize configuration, can optimize grain yield and quality and maintain high productivity even under water-limited conditions. Thus, it can be concluded that intercropping has significant alleviating effects on drought stress, improving both yield and quality. Therefore, in light of all these considerations, it can be posited that a less stressful agricultural environment with intercropping may potentially prompt a move towards more effective and nourishing food production.

Authors' Contributions

YOK: Methodology, Investigation, Data curation, Writing – review & editing. YA: Planning applications of the experiment, Writing – review & editing. IA: statistical analysis, interpretation, review & editing TG: Calculation of applied irrigation water and executed the experiments and data 458 collection.

All authors read and approved the final manuscript.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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