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Improving Water Use Efficiency and Economic Benefits of Cropping System Through Intercropping in an Arid Climate

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ABSTRACT

The sustainable increase of total productivity by improving resources use efficiency in arid agricultural farming areas is crucial, and intercropping may be a good practice to be implemented in these arid regions. For this purpose, a three-year field experiment was conducted as a randomized complete block design (RCBD) with three replications at the research farm of the Agricultural and Natural Resources Research Station of Gonabad, Gonabad, Iran to assess the agronomic and economic indices of intercropping patterns. The experiment treatments included C_1: sole cotton, C_2: sole sesame, and intercropping ratios (C_3: 20:80, C_4: 40:60, C_5: 50:50, C_6: 60:40, and C_7: 80:20 cotton-sesame ratio). The results showed that the leaf chlorophyll content and leaf area index were significantly higher in the intercropped plants compared to the sole cropped plants. The yield components of both crops (such as branches per plant, capsules per plant, seeds per capsule, and 1000-seed weight for sesame, and opened bolls per plant, closed boll per plant, and seed cotton per boll for cotton) significantly improved under intercropping. However, the highest sesame seed yield (2703, 1979, and 1358 kg ha^{-1}, respectively) and seed cotton yield (3749, 2179, and 3426 kg ha^{-1}, respectively) in the three experiment years were observed in the sole cropping treatment. The implementation of intercropping significantly improved the water use efficiency of the cropping system, so that the highest values in the first to third year (0.67, 0.51, and 0.41 kg m^{-3}, respectively) were recorded in the C_4, C_3, and C_7 treatments. The intercropping evaluation indices revealed the advantage of intercropping compared to the sole cropping. The highest value of the land equivalent ration in the first year (1.28) belonged to the C_4 treatment, while in the second and third years, belonged to the C_7 treatment (1.40 and 1.10, respectively). The calculation of the aggressivity index revealed that in most of the intercropping patterns, especially in the first and second years, cotton showed greater competitive ability than sesame. The highest actual yield loss value in the first year (0.64) belonged to the C_3 treatment, while in the second and third years, belonged to the C_7 treatment (1.42 and 0.34, respectively). The highest economic advantage in terms of the monetary advantage index in the first year was obtained by the C_4 treatment (1140.5), and in the second and third years, was observed in the C_7 treatment (940.6 and 265.5, respectively). The intercropping advantage index in the three experiment years was highest (1.41, 3.38, and 0.80, respectively) for the C_7 treatment. Eventually, the results of this research show that cotton and sesame are able to adapt well to the intercropping and this cropping system can significantly improve the resources use efficiency (especially water and land) in an arid area enjoying greater economic benefit than sole cropping.

Keywords: Land equivalent ratio, Economic evaluation, Environmental resources, Plant competition, Yield

1. Introduction

Due to global population growth and the ever-increasing demand for food, fiber, and fuel, it is necessary to enhance agricultural production by decreasing the environmental footprint of farming systems. The "Green Revolution" has enhanced agricultural production over the last decades, along with reducing starvation and food poverty. However, such changes have been accompanied by hazards and risks to ecosystems and living organisms. These risks may include increased pressure on environmental resources, air and soil pollution, fluctuation in crop yields and unstable production, genetic erosion and loss of biodiversity, and disruption to agricultural productivity and sustainability. The main reasons for these challenges are the introduction of genetically modified varieties and monoculture, the application of large amounts of fertilizers and chemical pesticides, and the use of auxiliary inputs (Cassman 1999; Cook 2006; Weekley et al. 2012).

For these reasons, it is necessary to revise conventional farming, utilize traditional and indigenous knowledge, and use ecologically-oriented techniques in crop production. In the future, farmers will have to produce more agricultural products with fewer environmental resources (Schneider et al. 2011). Polyculture systems, particularly intercropping, as a crop diversification technique, is an example of this type of system that has long been in use (Liu 1994; Innis 1997). These systems have been exploited to optimize the utilization of environmental resources such as land, light, water, and nutrients by manipulating in-farm components and the interactions within the agroecosystem to ultimately improve crop productivity, stability, and sustainability of agroecosystems (Mushagalusa et al. 2008; Mao et al. 2012; Ning et al. 2017). Considering the arid and semi-arid climate of most areas of Iran and the vulnerability of agriculture to various environmental hazards, these types of agricultural systems have had a special place in Iran's traditional agriculture and have effectively helped farmers to adapt to the climate.

Despite polyculture and intercropping having a long history in Iran, less attention has been paid to these cropping systems, especially in the study area. The departure from the traditional agricultural operations to the modern ones in Iran, and the negligence of indigenous agricultural knowledge on the one hand, and the development of monoculture systems and excessive dependence on off-farm inputs, especially chemical fertilizers and pesticides, on the other hand, have all been considered as minatory factors in Iran's agriculture. Thus, the present study evaluates the agronomic and economic aspects of intercropping systems of two main field crops (i.e., cotton and sesame) cultivated in the northeast of Iran.

2. Material and Methods

2.1. The features of study area

The field experiments were conducted for three consecutive years (2016-2018) at the research farm of the Agricultural and Natural Resources Research Station of Gonabad, Khorasan Razavi province, Iran (57º45' N; 51º10' E; 1056 m a.s.l.). The area has a mean annual temperature of 11.5 ˚C and the total number of frost days during the cropping year is 33. Based on the Köppen climate classification, the climate of the area is arid, characterized by high temperatures during mid-spring to late summer, and low temperatures during mid-fall to late winter, with an average annual precipitation of 146 mm mostly concentrated in winter and early spring and a potential pan evaporation of 2021 mm (IRIMO 2018).

2.2. Experiment design and field management

A randomized complete block design with three replications was used with the following treatments: C_1: sole cotton, C_2: sole sesame, and intercrop patterns including C_3: 20:80, C_4: 40:60, C_5: 50:50, C_6: 60:40, and C_7: 80:20 cotton: sesame ratio, respectively.

Before implementing the design, the soil samples at the experimental field from the 0-30 cm soil depth were collected and transferred to the laboratory. Some physicochemical properties of the experimental soil are shown in Table 1. Cotton and sesame were sowed simultaneously in both intercropping and sole cropping patterns. The area of each plot was 30 m^2 (6 m × 5 m). The inter-row distance for each plant was 50 cm, and the inter-plant distance was 15 and 30 cm for sesame and cotton, respectively. Immediately after sowing, the plots were irrigated using the furrow irrigation method. To ensure uniform emergence, the second irrigation was performed three days after the first irrigation. Further irrigation was carried out according to the custom of the area at 8-day intervals. The irrigation water used was supplied from a ground water well located in the research farm. Some chemical properties of the irrigation water are presented in Table 2. To control weeds, two stages of hand weeding were conducted during each growing season. No specific pests or diseases were observed in the field during the study period.

Table 1- Physicochemical properties of the experimental soil

Soil texture	*Organic carbon*	*Total N*	*Available P*	*Available K*	*EC*	*pH*
-	*%*		*mg kg^{-1}*		*dS m^{-1}*	-
Sandy loam	0.18	0.045	18.8	271	1.54	7.7

Table 2- Chemical properties of the irrigation water applied

Ca+Mg	*Na*	*Cl*	*SAR*	*TDS*	*EC*	*pH*
meq L^{-1}			-	*mg L^{-1}*	*dS m^{-1}*	-
10.3	9.2	15.4	8.5	1856	2.5	7.5

2.3. Data collection and intercropping evaluations

The leaf chlorophyll content of the crops was recorded at the flowering stage using a SPAD chlorophyll meter (SPAD 502, Minolta Ltd., Japan). The leaf area of each crop was measured at the flowering stage using a leaf area meter (LI-3100C), and the leaf area index (LAI) was calculated as follows (Chimonyo et al. 2016):

$$\mathrm{LAI} = \frac{\mathrm{LA}}{\mathrm{A}}$$

Where: LA is the plant leaf area (m^2), and A is the land area occupied by the plant (m^2). Five randomly selected plants were used to record leaf chlorophyll content and leaf area index.

The yield components for each crop were measured using ten randomly selected plants in each plot. The seed cotton of fully opened and matured bolls in the four central rows of each plot was hand-harvested two times each year, and was then weighted and calculated as kg ha^{-1}. The lint percentage was measured after ginning the cotton bolls.

When the sesame plants were yellowish, and their capsules had not cracked, the plants in the four central rows were harvested and air-dried. Then, the seeds were separated from the capsules, weighted, and converted into seed yield (kg ha^{-1}).

The total volume of water used for irrigation was measured by a volumetric water meter connected to irrigation pipes so that the total amounts of water used during the first to third experiment years were 4700, 4050, and 4100 m^3 ha^{-1} for sesame, and 8400, 7750, and 7900 m^3 ha^{-1} for cotton, respectively. The water use efficiency (WUE) of both crops was calculated using the following formula (Kang et al. 2000):

$$\mathrm{WUE} = \frac{\mathrm{EY}}{\mathrm{IW}}$$

Where: EY is the economic yield (kg ha^{-1}), and IW is the irrigation water used (m^3 ha^{-1}).

The agronomic and economic indices used for the comparison between the intercropping and sole cropping systems are listed in Table 3.

Table 3- List of agronomic and economic indices used to assess the cotton-sesame intercropping

Index	***Formula***	***Reference***
Agronomic indices		
Land equivalent ratio (LER)	$\mathrm{LER} = \mathrm{LER_{cot}} + \mathrm{LER_{ses}} = \frac{\mathrm{Y_{int,cot}}}{\mathrm{Y}_{sole,\mathrm{cot}}} + \frac{\mathrm{Y_{int,ses}}}{\mathrm{Y}_{sole,\mathrm{ses}}}$	Willey & Rao (1980)
Aggressivity (A)	$\mathrm{A_{cot/ses}} = \frac{\mathrm{Y_{int,cot}}}{\mathrm{Y}_{sole,\mathrm{cot}} \times \mathrm{F_{cot}}} - \frac{\mathrm{Y_{int,ses}}}{\mathrm{Y}_{sole,\mathrm{ses}} \times \mathrm{F_{ses}}}$	Banik et al. (2000)
Actual yield loss (AYL)	$\mathrm{AYL} = \mathrm{AYL_{cot}} + \mathrm{AYL_{ses}}$ $\mathrm{AYL_{cot}} = \left[\frac{\mathrm{Y_{int,cot}}}{\mathrm{F_{int,cot}}} \Big/ \frac{\mathrm{Y}_{sole,\mathrm{cot}}}{\mathrm{F}_{sole,\mathrm{cot}}}\right] - 1$ $\mathrm{AYL_{ses}} = \left[\frac{\mathrm{Y_{int,ses}}}{\mathrm{F_{int,ses}}} \Big/ \frac{\mathrm{Y_{sole,ses}}}{\mathrm{F}_{sole,\mathrm{ses}}}\right] - 1$	Banik (1996)
Economic indices		
Monetary advantage index (MAI)	$\mathrm{MAI} = \left[(\mathrm{Y_{int,cot}} \times \mathrm{P_{cot}}) + (\mathrm{Y_{int,ses}} \times \mathrm{P_{ses}})\right] \times \left[\frac{\mathrm{LER} - 1}{\mathrm{LER}}\right]$	Ghosh (2004)
Intercropping advantage (IA)	$\mathrm{IA} = \mathrm{IA_{cot}} + \mathrm{IA_{ses}}$ $\mathrm{IA_{cot}} = \mathrm{AYL_{cot}} \times \mathrm{P_{cot}}$ $\mathrm{IA_{ses}} = \mathrm{AYL_{ses}} \times \mathrm{P_{ses}}$	Banik et al. (2000)

$Y_{int,cot}$ and $Y_{int,ses}$ represent the yields of cotton and sesame under intercropping, while, $Y_{sole,cot}$ and $Y_{sole,ses}$ express the respective yields under sole cropping, respectively; F_{cot} and F_{ses} are the plant proportion (%) of cotton to sesame and of sesame to cotton in the intercropping, respectively; P_{cot} and P_{ses} represent the commercial value of cotton and sesame, respectively

2.4. Statistical analysis

The data were analyzed using the analysis of variance (ANOVA) in the SAS statistical package version 9.1. The means differences were identified using the least significant difference multiple range tests (LSD) at a 5% significance level.

3. Results and Discussion

3.1. Sesame

The analysis of variance for the data from the three experiment years indicated significant differences in the traits of sesame plants grown under sole and intercropping systems. The data in Table 4 clearly show that the plants grown under the intercropping system had higher chlorophyll content than the sole-cropped plants. The highest value (47.0, 42.5, and 56.1 for the first to third experiment year, respectively) was obtained from the C_5 treatment (50:50 cotton-sesame intercropping). Weisany et al. (2015) found that growing crops under an intercropping system led to an increase in the chlorophyll content by improving nutrient availability.

The leaf area index (LAI) of the sesame plants was significantly influenced by the cropping systems. As shown in Table 4, variations in the response of the LAI to the sole and intercropping patterns were observed during the three years of the experiment, so that the highest value in the first year (4.2) belonged to the sole sesame, while in the second and third years, the C_6 treatment (60:40 cotton-sesame intercropping) resulted in the highest value (3.1 and 2.7, respectively).

The results of our experiment showed that in the three experiment years, the height of the sesame grown under sole cropping (89.9, 116.3, and 111.3 cm, respectively) or 20:80 cotton-sesame intercropping pattern (96.7, 114.7, and 109.7 cm, respectively) was higher than plants grown under other cropping systems. The height of the sesame plants increased depending on its ratio in the mixture (Table 4). The increased height of plants in the sole sesame treatment, as well as the intercropping pattern with high sesame proportion maybe due to intra-specific competition between individual plants for light. Since light does not reach the lower layer of the crop canopy, auxin does not decompose, and thus its increased concentration leads to stem elongation (Cruz & Sinoquet 2003). Basaran et al. (2017) found a plant height increase compared to sole cropping in sorghum-sudangrass hybrid intercropped with legumes.

The number of lateral branches of sesame in the experimental years (with the exception of the second year) showed a significant response to the cropping systems. The values of this trait were higher in intercropping treatments and especially in patterns with a lower proportion of sesame rather than cotton. The highest value for the three experiment years (44.3, 32.7, and 44.9, respectively) belonged to the C_7 treatment (Table 4). In addition, the intercropping of sesame with cotton significantly enhanced the number of capsules per plant so that the highest values for the three experiment years (167.4, 183.4, and 172.1, respectively) belonged to the C_7 treatment, followed by the C_6 treatment (Table 4). The ANOVA results showed that the effects of the experimental treatments on the number of seeds per capsule in the first and second years were significant, but were not significant in the third year. The best results for the three years (63.5, 69.0, and 68.0, respectively) were obtained from the C_7 treatment, followed by the C_6 treatment (Table 4). The improved sesame traits under these intercropping systems may be due to the different niches being occupied by the intercrop components, especially root distribution and aboveground architecture, which tend to enhance the use of available environmental resources (e.g., water, nutrients, and solar radiation) through complementary relationships, ultimately increasing crop productivity and resource use efficiency (Li et al. 2011; Lithourgidis et al. 2011).

As presented in Table 4, the cropping systems had no significant effect on the 1000-seed weight of sesame. Similarly, de Araújo et al. (2013) reported no significant difference between the sole and intercropping systems of sesame and cowpea for this trait.

Table 4- Physiological properties and yield components of sesame under sole and intercropping systems

Treatments / Year	*Branch per plant*			*Capsule per plant*			*Seed per capsule*			*1000-seed wt. (g)*		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
C_2	39.6bc	31.7	33.9c	152.7c	168.1c	153.9b	62.2ab	62.3c	57.9	3.1	3.3	4.0
C_3	37.0c	28.0	36.0bc	147.9c	162.3c	156.0b	55.9c	62.4c	60.5	3.1	3.3	3.8
C_4	45.4a	31.3	39.3abc	152.9c	169.2bc	164.0ab	58.0bc	64.0bc	61.7	3.1	3.3	4.1
C_5	43.1ab	31.7	43.3ab	157.2bc	173.0abc	163.7ab	58.5bc	65.5bc	63.2	3.0	3.4	3.6
C_6	44.9a	32.0	44.4a	163.8ab	179.7ab	171.0a	66.7a	68.1ab	59.3	3.2	3.3	4.2
C_7	44.3a	32.7	44.9a	167.4a	183.4a	172.1a	63.5a	69.0a	68.0	2.9	3.4	3.8
LSD 5%	4.737**	5.077ns	8.109*	10.254*	10.922**	11.422*	4.616**	4.182**	11.789ns	0.354ns	0.436ns	1.280ns

Table 4 (Continue)- Physiological properties and yield components of sesame under sole and intercropping systems

Treatments / Year	*Chlorophyll content (SPAD value)*			*LAI*			*Plant Height (cm)*		
	1st	*2nd*	*3rd*	*1st*	*2nd*	*3rd*	*1st*	*2nd*	*3rd*
C_2	42.9	37.5b	45.2b	4.2a	2.56bc	1.7b	89.9a	116.3	111.3a
C_3	44.1	37.2b	44.1b	3.0bc	3.0ab	2.0ab	96.7a	114.7	109.7a
C_4	42.3	39.8ab	55.5a	2.8bc	3.0ab	1.7b	86.5ab	114.1	107.3ab
C_5	47.0	42.5a	56.1a	2.4c	2.9ab	2.7a	76.3b	113.0	94.3c
C_6	45.8	39.4ab	52.8a	3.7ab	3.1a	2.7a	84.5ab	113.1	99.0bc
C_7	44.8	41.3a	55.9a	3.3abc	2.3c	2.0ab	75.8b	113.0	108.0ab
LSD 5%	7.554ns	3.639*	3.979***	1.067*	0.477*	0.753*	13.44*	4.962ns	10.417*

*, **, ***: and ns indicate statistical differences at $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$, and non-significant, respectively. The columns with the same letter are not significantly different at $P \leq 0.05$, according to Duncan's multiple range tests. C_2 to C_7 will be used for sole sesame, 20:80, 40:60, 50:50, 60:40, and 80:20 cotton-sesame intercropping treatments, respectively

Sesame seed yield showed a significant difference under the influence of experimental treatments. The highest seed yield was obtained when the plants were grown under sole cropping. The sesame seed yield decreased depending on its ratio in the mixture, so that its value in the C_7 treatment was 67.0%, 57.5%, and 77.5% lower than that of the sole crop in the three years of the experiment, respectively (Figure 1). This was to be expected because the density of sesame in the sole cropping pattern was the highest, and with the reduction of the proportion of sesame in intercropping, the density of the plant per unit area also decreased. Similar to these findings, Khan et al. (2017) reported a reduction in the seed yield of sesame under the intercropping system compared to monocropping in sesame-groundnut intercrop.

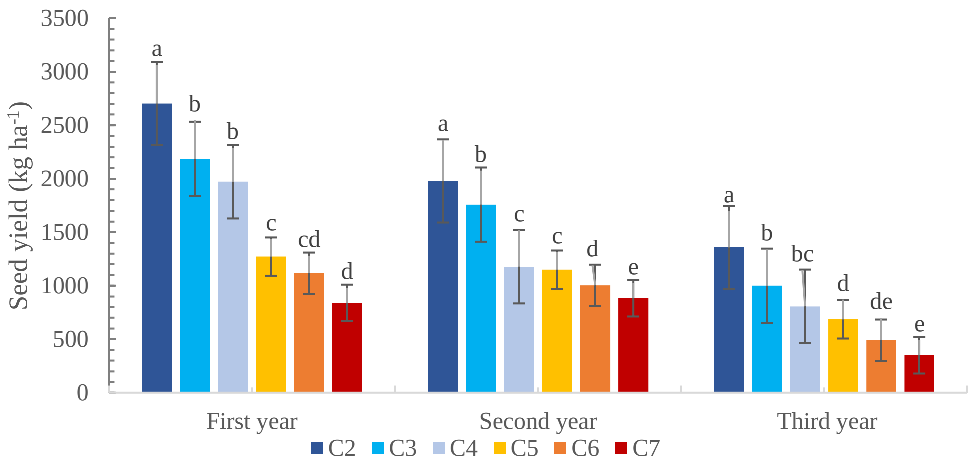

Figure 1- Sesame seed yield sesame under sole and intercropping systems
The same letters are not significantly different at $P \leq 0.05$ according to Duncan's multiple-range tests

3.2. Cotton

The analysis of variance of the experimental data revealed that the cotton traits were significantly affected by the cropping system treatments. As presented in Table 5, the leaf chlorophyll content was lower in the plants grown under the sole cropping system in all the experiment years. However, the difference between the treatments was not significant in the first year, whereas, the SPAD values were higher in treatments with a lower proportion of cotton than sesame, especially in the C_3 treatment (51.2, 38.5, and 44.1 for the experiment years, respectively) (Table 5). This result may be due to an increased nutrient availability, uptake, and mobility in intercropping systems, which can lead to enhanced chlorophyll synthesis in leaves (Liu et al. 2014). Another reason for the higher chlorophyll content in the intercropped cotton plants compared to sole crops can be the difference in the canopy structure (spatial niche differentiation), which causes more light absorption, or in other words, increases the light use efficiency (Wang et al. 2021), and ultimately enhances the synthesis of chlorophyll (Nasar et al. 2022).

Table 5- Physiological properties and yield components of cotton under sole and intercropping systems

Treatments / Year	*Chlorophyll content (SPAD value)*			*LAI*			*Plant Height (cm)*		
	1st	*2nd*	*3rd*	*1st*	*2nd*	*3rd*	*1st*	*2nd*	*3rd*
C_2	42.9	37.5b	45.2b	4.2a	2.56bc	1.7b	89.9a	116.3	111.3a
C_3	44.1	37.2b	44.1b	3.0bc	3.0ab	2.0ab	96.7a	114.7	109.7a
C_4	42.3	39.8ab	55.5a	2.8bc	3.0ab	1.7b	86.5ab	114.1	107.3ab
C_5	47.0	42.5a	56.1a	2.4c	2.9ab	2.7a	76.3b	113.0	94.3c
C_6	45.8	39.4ab	52.8a	3.7ab	3.1a	2.7a	84.5ab	113.1	99.0bc
C_7	44.8	41.3a	55.9a	3.3abc	2.3c	2.0ab	75.8b	113.0	108.0ab
LSD 5%	7.554ns	3.639*	3.979***	1.067*	0.477*	0.753*	13.44*	4.962ns	10.417*

Table 5 (Continue)- Physiological properties and yield components of cotton under sole and intercropping systems

Treatments / Year	*Chlorophyll content (SPAD value)*			*LAI*			*Earliness (%)*			*Plant Height (cm)*		
	1st	*2nd*	*3rd*	*1st*	*2nd*	*3rd*	*1st*	*2nd*	*3rd*	*1st*	*2nd*	*3rd*
C_1	51.2	38.5^{ab}	44.1^{bc}	3.4^{ab}	2.3^{b}	3.3^{ab}	85.6	66.6^{a}	63.7^{ab}	64.2^{a}	68.7^{a}	108.3^{a}
C_3	59.5	40.2^{a}	52.0^{a}	3.6^{a}	2.4^{ab}	3.6^{a}	83.3	57.3^{b}	55.4^{b}	46.6^{c}	41.7^{d}	$10.1.3^{a}$
C_4	59.5	38.8^{a}	49.4^{ab}	3.3^{ab}	2.7^{a}	3.4^{a}	81.1	57.6^{b}	55.6^{b}	47.4^{bc}	42.3^{cd}	98.7^{ab}
C_5	50.8	34.4^{cd}	48.6^{abc}	2.9^{bc}	2.3^{b}	2.9^{bc}	86.3	60.9^{ab}	60.3^{b}	44.9^{c}	45.3^{c}	88.3^{b}
C_6	53.1	31.6^{d}	$48.^{abc}$	3.1^{abc}	1.9^{c}	2.8^{c}	86.8	65.1^{a}	61.7^{b}	60.9^{ab}	49.7^{b}	98.0^{ab}
C_7	54.4	35.3^{bc}	43.3^{abc}	2.7^{c}	2.5^{ab}	2.8^{c}	85.9	61.1^{ab}	72.7^{a}	57.1^{abc}	66.3^{a}	101.7^{a}
LSD 5%	11.0^{ns}	3.448^{***}	5.743^{*}	0.578^{*}	0.343^{**}	0.471^{**}	7.049^{ns}	6.147^{*}	10.828^{*}	13.982^{*}	3.044^{***}	11.223^{*}

*, **, ***: and ns indicate statistical differences at $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$, and non-significant, respectively. The columns with the same letter are not significantly different at $P \leq 0.05$, according to Duncan's multiple range tests. C_1 to C_7 will be used for sole cotton, 20:80, 40:60, 50:50, 60:40, and 80:20 cotton-sesame intercropping treatments, respectively

According to the results (Table 5), the leaf area index (LAI) was also higher in intercropped cottons than in sole-cropped ones. The C_3 treatment in the first and third year of the experiment resulted in the highest LAI (3.6 and 3.6, respectively), while in the second year, the C_4 treatment achieved the highest value (2.7).

The effect of the experimental treatments on the earliness of cotton in the first experiment year was not significant, while its effect in the second and third years was significant (Table 5). The C_1 and C_6 treatments in the second year resulted in the highest values of this trait (66.6 and 65.1%, respectively), while in the third year, the C_7 treatment showed the highest value (72.7%).

The cotton height varied significantly under the influence of cropping systems. Similar to sesame, the cotton plants grown under sole cropping had the highest value (64.2, 68.7, and 108.3 cm, for the first to third year, respectively), followed by the C_7 treatment. The height of the cotton increased depending on its ratio in the mixture (Table 5). These results are in agreement with the findings of Iqbal et al. (2007), who reported that the plant height of cotton under sole cropping and intercropped with sesame in high cotton density was significantly higher than cotton plants intercropped in low density. Taranenko et al. (2021) determined that the shading effect of the intercrop component with higher density and height is the main reason for plant height reduction of another crop component in intercrop.

The data presented in Table 5 indicate that the number of opened bolls per plant had the highest value in the three experiment years (10.9, 9.2, and 11.0, respectively) as affected by the C_3 treatment, followed by the C_4 treatment. The highest number of closed bolls per plant in the first year (1.13) was obtained by implementing the C_4 treatment, while in the second and third years, the highest values (1.53 and 2.13, respectively) were obtained as a result of the C_3 treatment (Table 5). These findings reveal the above and under-ground interference effects of cropping systems and that inter-specific competition between the two species was less than intra-specific competition between cotton plants in 20:80 and 40:60 mixtures compared to sole cotton and other intercropping systems (Hadejia 2011).

The seed cotton weight per boll in the first year did not show a significant variation under the cropping systems. While in the second and third years, the difference between the treatments was significant. Table 5 shows that in the second and third years, the highest seed cotton weight per boll (3.98 and 5.25 g, respectively) was observed due to the C_3 treatment.

Figure 2 shows that the seed cotton yield achieved in sole cropping (3749, 2179, and 3426 kg ha^{-1} for the first to third year, respectively) was significantly higher compared to the intercropped cotton; the C_7 treatment had the highest seed cotton yield (2703, 1980, and 2641 kg ha^{-1}, respectively) among the intercropping patterns. As the proportion of cotton decreased in the intercrop, the seed cotton yield decreased gradually. The main reason for the decrease in crop yield under intercropping compared to sole cropping was the decrease in plant density in the intercropping patterns. Other researchers have reported a reduction in crop yield under intercropping compared to sole cropping. However, the significantly lower seed cotton yield in intercropping should not overshadow the advantages of intercropping systems in total yield (Jahansooz et al. 2007).

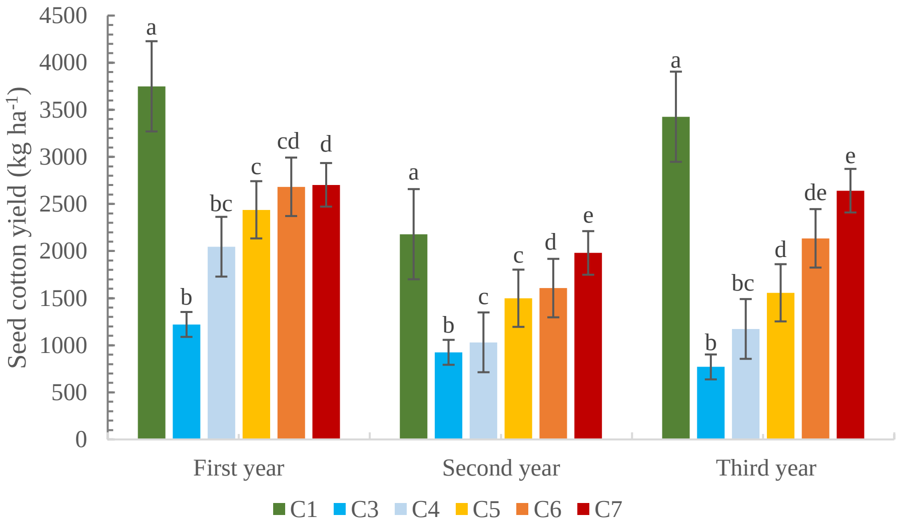

Figure 2-Seed cotton yield under sole and intercropping systems

The same letters are not significantly different at P≤0.05, according to Duncan's multiple-range tests

Based on the results (Figure 3), the lint percentage significantly increased when cotton plants were intercropped compared to those sole-cropped. The highest lint percentage in the three years of the experiment (39.2, 39.6, and 40.7%, respectively) was recorded in the C_3 treatment, while the lowest value was observed in the sole cotton (36.5, 36.0, and 36.0%, respectively). Other researchers (Wang et al. 2021) have reported an improvement in lint percentage in intercropped over sole-cropped cotton

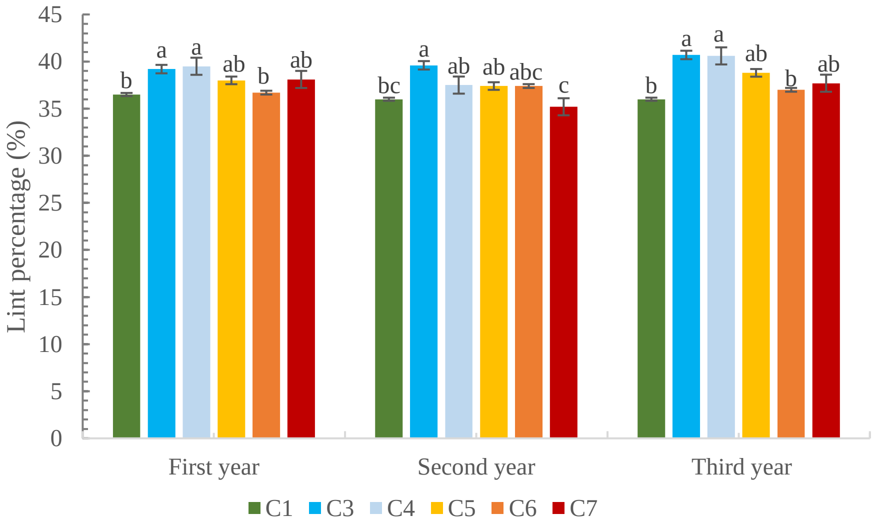

Figure 3- Cotton lint percentage under sole and intercropping systems

The same letters are not significantly different at P≤0.05, according to Duncan's multiple-range tests

3.3. *Water use efficiency (WUE)*

Figure 4 presents a comparison of means between treatments in terms of water use efficiency (WUE). Based on the results, the implementation of intercropping significantly increased the WUE of the cropping system. However, in the three experiment years, different results were obtained in terms of the highest value of WUE, and the C_4, C_3, and C_7 treatments achieved the highest value (0.67, 0.51, and 0.41 kg m^{-3}, respectively) from the first to the third year of the experiment, respectively. The different influences of intercropping systems on WUE may be due to environmental and climatic conditions, soil characteristics, and crop characteristics (Xu et al. 2008). Some researchers have noted that when component crops are properly selected in intercropping, improvements in resource use efficiency can be achieved (Dong et al. 2018). Consequently, the physiological factors at the field level, such as community structure and diversity (Above-ground and below-ground biomass), which have led to better use of resources, especially water and light, can be considered important reasons for increasing the water use efficiency of intercropping systems (de Barros et al. 2007; Li et al. 2020). Differences in the temporal and spatial water requirement of each intercrop component during the growing season may be another reason for the high WUE of intercropping (Bai et al. 2016). The mean comparison also showed that the lowest value in the first and second years was obtained from the sole-cropped cotton (0.45 and 0.27 kg m^{-3}, respectively), while in the third year, the lowest value was observed in the sole-cropped sesame (0.30 kg m^{-3}). The main reason for this result can be attributed to the significantly low yield of sesame in the third year of the experiment.

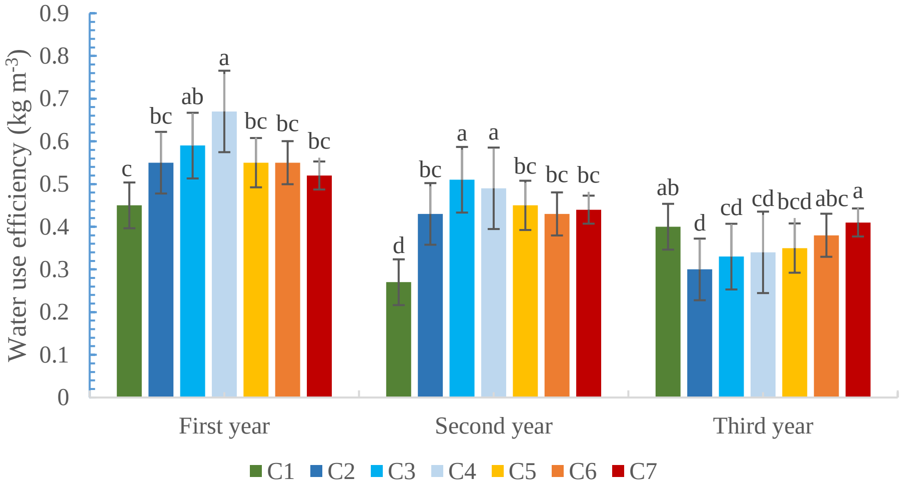

Figure 4- Water use efficiency of the cropping systems under sole and intercropping systems
The same letters are not significantly different at P≤0.05, according to Duncan's multiple-range tests

3.4. *Land equivalent ratio (LER)*

The most important index used to compare intercropping systems with sole cropping is the land equivalent ratio (LER). Calculating the partial LER for sesame indicated that the best result for the three experiment years (0.81, 0.89, and 0.74, respectively) was obtained from the C_3 treatment, while the C_7 treatment showed the highest LER for cotton (0.78, 0.95, and 0.84, respectively). The LER for each crop decreased depending on its ratio in the mixture, so the lowest LER values for sesame and cotton belonged to the 80:20 and 20:80 cotton-sesame intercrop, respectively (Table 6). According to the results (Table 6), the total LER values of all the intercropping patterns were greater than 1 (except for the C_4 treatment in the third year with a value of 0.96), revealing that implementing intercropping systems resulted in higher yield per unit area compared to sole cropping. In other words, the productivity and efficiency of the intercropping systems were higher than the sole cropping systems (Živanov et al. 2018). Table 6 shows that the LER values for different cropping patterns were almost equal, revealing that crop yield reduction of each intercrop component was compensated by another component, ultimately contributing to the constant increase of the LER. Improvements in the LER under intercropping compared to sole cropping systems have also been reported by other studies (Nandini & Chellamuthu 2004; Reddy & Mohammad 2009; Velmurugan & Ravinder 2012; Yilmaz et al. 2015; Ibrahim & Acikalin 2020). This productivity improvement maybe due to decreased competitiveness and spatially and temporally complimentary use of environmental resources such as light, water, and nutrients (Willey 1990). However, contrary to our findings, Momirović et al. (2015) reported LER values below 1 and no improvements in the land use efficiency of maize-pumpkin intercrops compared with sole crops.

Table 6- Land equivalent ratio (LER) of cotton-sesame intercropping systems

Treatments / *Year*	*Cotton*			*Sesame*			*Total*		
	1st	*2nd*	*3rd*	*1st*	*2nd*	*3rd*	*1st*	*2nd*	*3rd*
C_3	0.33	0.44	0.28	0.81	0.89	0.74	1.14	1.31	1.02
C_4	0.55	0.50	0.37	0.73	0.60	0.59	1.28	1.10	0.96
C_5	0.65	0.72	0.49	0.47	0.58	0.54	1.12	1.30	1.03
C_6	0.72	0.77	0.68	0.41	0.51	0.36	1.13	1.28	1.04
C_7	0.78	0.95	0.84	0.31	0.45	0.26	1.09	1.40	1.10

3.5. *Aggressivity (A)*

A positive aggressivity index for a species indicates its higher aggressivity and dominance over other species, while a negative index indicates the aggressivity of other species. An aggressivity value of zero indicates equilibrium between interspecific and intraspecific competition, leading to non-dominance between species (Ghosh 2004). Table 7 shows that in most intercropping systems, cotton was dominant over sesame, and this dominance was higher in the intercrop patterns with lower cotton proportions. The highest aggressivity value during the experiment years (0.62, 1.1, and 0.46, respectively) was found in the C_3 treatment, while the C_7 treatment showed negative values indicating sesame dominance over cotton. The aggressivity of cotton reflects the plant's ability for better and more efficient use of environmental resources, especially soil nutrients and light (Matusso et al. 2014; Rostaei et al. 2018).

Table 7- Cotton aggressivity (A) and actual yield loss (AYL) of cotton-sesame intercropping systems

Treatments	*A*			*AYL*								
	Cotton			*Cotton*			*Sesame*			*Total*		
Year	*1st*	*2nd*	*3rd*	*1st*	*2nd*	*3rd*	*1st*	*2nd*	*3rd*	*1st*	*2nd*	*3rd*
C_3	0.62	1.11	0.46	0.63	1.22	0.38	0.01	0.11	-0.08	0.64	1.33	0.30
C_4	0.14	0.25	-0.06	0.36	0.24	-0.07	0.22	-0.01	-0.01	0.58	0.23	-0.08
C_5	0.36	0.28	-0.02	0.30	0.44	-0.01	-0.06	0.16	0.01	0.24	0.60	0.00
C_6	0.16	0.02	0.23	0.19	0.29	0.13	0.03	0.27	-0.09	0.22	0.56	0.03
C_7	-0.58	-1.04	-0.24	-0.03	0.19	0.05	0.55	1.23	0.29	0.52	1.42	0.34

3.6. Actual yield loss (AYL)

Actual yield loss is used to evaluate each species in intercropping, indicating the importance of intra-specific and inter-specific competition, and the behavior of component crops in a cropping system. AYL represents a decrease in the actual yield of any intercrop component compared to the sole crop based on crop proportion. AYL provides more comprehensive information on crop competition relative to other intercropping indices (Banik et al. 2000). The data in Table 7 show that this index was positive for both crops in most of the intercropping systems, particularly for cotton, indicating the effect of intercropping on increasing actual yield. The highest values for cotton and sesame during the first to third years were observed in the C_3 (0.63, 1.22, and 0.38, respectively) and C_7 treatment (0.55, 1.23, and 0.29, respectively). According to the average of the data obtained from our three-year experiment (Table 7), all the intercropping systems (except for the C_4 treatment in the third year) achieved positive total AYL values, revealing lower inter-specific competition than intra-specific competition as well as better adaptability of both crops under intercropping. Our results also showed that increased biodiversity in the intercropping system led to enhanced resource use efficiency compared to sole cropping (Ghosh et al. 2006). The advantage of intercropping compared to sole cropping in this experiment may also be based on the "Competitive Production Principle", revealing the possibility of better use of environmental resources through utilizing different intercropping components with different morphology, physiology, and ecology (Vandermeer 1990).

3.7. *Monetary advantage index (MAI)*

A positive MAI indicates a definite economic advantage for intercropping while negative values show a disadvantage for an intercropping system. This index was positive in all the intercropping systems (except for the C_4 treatment in the third year), which showed an economic advantage under intercropping compared to sole cropping, implying the general suitability of this polyculture production system due to the efficient use of environmental resources and the higher total crop yield achieved by intercropping. Our results show that the most profitable mixture in the first experiment year (1140.5) was the 40:60 cotton-sesame intercrop, and for the second and third years (940.6 and 265.5, respectively), it was found in the 80:20 mixture (Table 8). The higher monetary advantage in intercropping systems can be due to the higher production efficiency and crop value (Verma et al. 2013). Alabi & Esobhawan (2006) evaluated economic indices of maize-cotton intercrops and reported a 10% economic advantage for intercropping over sole cropping. The authors of that study believed that this economic advantage maybe the reason why farmers continue to grow these crops together.

Table 8- Monetary advantage index (MAI) and intercropping advantage (IA) of cotton-sesame intercropping systems

Treatments	*MAI*			*IA*		
Year	*1st*	*2nd*	*3rd*	*1st*	*2nd*	*3rd*
C_3	594.0	908.4	45.8	0.59	1.39	0.13
C_4	1140.5	267.5	-96.3	0.90	0.19	0.09
C_5	468.2	765.0	71.8	0.11	0.82	0.01
C_6	497.4	691.9	103.3	0.25	0.96	-0.15
C_7	335.5	940.6	265.5	1.41	3.38	0.80

3.8. Intercropping advantage (IA)

Another index that shows the economic feasibility of intercropping is Intercropping advantage (IA). Positive values indicate the economic advantage of intercropping, and negative values indicate the disadvantage of intercropping over sole cropping (Banik et al. 2000). As shown in Table 8, all the intercropping treatments (except for the C_6 treatment in the third year) showed positive values, indicating the economic advantage of intercropping compared to sole cropping. The highest values for the three years of the experiment (1.41, 3.38, and 0.80, respectively) were obtained through the implementation of the 80:20 cotton-sesame pattern. The results of a 2022 study (Wang et al. 2022) conducted on the economic evaluation of intercropping of cotton with peanuts showed that intercropping reduced costs and increased resource use efficiency and finally increased the farm's net income. The authors stated that the intercropping system could not only increase the crop yield per unit area but also provide notable economic benefits, which increase farmers' tendency to favor implementing intercropping rather than sole cropping in cotton cultivation (Wang et al. 2022).

4. Conclusions

Based on our findings, intercropping led to improvements in most of the growth indices (LAI and plant height) and yield components of sesame (branch per plant, capsule per plant, seed per capsule) and cotton (opened and closed boll, seed cotton per boll). The main reason for these results may be lowered plant density and decreased intraspecific competition between individual plants. While crop yields of sesame and cotton were significantly higher in sole cropping due to the harvest of more plants per unit area, the advantage indexes for intercropping highlighted its profitability. All the intercropping patterns achieved the LER values above 1, revealing high land use efficiency and the agronomic advantage of these cropping systems. In most treatments, cotton was dominant over sesame due to its high aggressivity, which represents the competitive ability and resource use efficiency of cotton compared to sesame. The AYL index showed positive values, revealing the yield advantage of intercropping compared to sole cropping. An evaluation of the economic advantage indices of intercropping also demonstrated that in most of the intercropping patterns during the three experiment years, the MAI and IA index showed positive values, which indicate the economic preference for intercropping over sole cropping.

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