Legume crops enhance water use efficiency under intercropping system with wheat

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Abstract

A comparative analysis of three legume crops (faba bean, peas, and clover) as intercrops with wheat was conducted under three irrigation treatments (100%, 85%, and 70% ETc) to evaluate their contributions to enhancing the complementary effect that improves water usage and wheat production. The irrigation water applied to wheat intercropping systems was equivalent to that applied to sole wheat, indicating that both intercrops utilized the irrigation designated for sole wheat. The faba bean-wheat intercropping system exhibited the greatest water utilization and soil accessible nitrogen across the three irrigation regimens. The production of intercropped wheat was maximized in the peas intercropping system, in contrast to the yield of sole wheat. The intercropping system of peas achieved the highest land equivalent ratio (LER), water equivalent ratio (WER), and change in water use, indicating enhanced water use efficiency. In an irrigation scenario of 85% ETc, the LER and WER for the peas intercropping system exceeded those of the faba bean intercropping system under 100% ETc. The intercropping system with peas had the highest monetary advantage index value. This suggests that, in the context of limited water resources, intercropping peas with wheat is advisable to enhance the utilization of available water resources.

Keywords: Faba bean, peas, clover, available soil N, land and water equivalent ratios, change in water use, momentary advantage index

INTRODUCTION

Agriculture is the predominant consumer of freshwater globally, accounting for about two-thirds of total withdrawals (Gan *et al*., 2013). Due to the scarcity of freshwater resources in arid and semiarid regions globally (Forouzani and Karami, 2011), agricultural water allocation must be re-evaluated to meet the developmental demands of other sectors (Chai *et al*., 2016). The IPCC (2013) indicated that climate change is anticipated to exacerbate stress on water resources, since alterations in precipitation and temperature may result in variations in runoff and water availability (Cisneros *et al*., 2014). Prior studies indicated that climate change will exacerbate and hasten the hydrological cycle, leading to increased water availability in certain regions while diminishing it in the majority of developing nations (IPCC, 2013). Therefore, enhancing the efficiency of agricultural water resource utilization and mitigating excessive irrigation would be imperative.

Intercropping is an agroecological technique that entails the simultaneous cultivation of two or more crops in the same field for a portion or the entirety of the growing season (Bedoussac *et al*., 2015). Legume-cereal intercropping systems provide various advantageous agroecological effects: they increase crop diversification and farm nitrogen self-sufficiency (Tosti *et al*., 2023), enhance soil health (Ditzler *et al*., 2021), manage pests and weeds (Daryanto *et al*., 2020), and reduce yield loss while ensuring yield stability (Koskey *et al*., 2022). The land equivalent ratio, a measure that assesses the overall net impact on total biomass produced by intercrops, is typically higher in legume-cereal intercropping systems than in monoculture (Ivanov *et al*., 2012). Moreover, legume-cereal intercropping systems enhance the sustainable use of water resources and augment water production, as the irrigation water allocated to the primary crops is utilized by both intercrops (Qin *et al*., 2013; Yang *et al*., 2011). Soil evaporation and soil water content were diminished with the intercropping system in comparison to sole planting (Rahman *et al*., 2017). Hu *et al*., (2015) discovered that intercropping systems utilize more water and improve water use efficiency by an average of 26%. Moreover, Coll *et al*., (2012) elucidated that the enhancement of water production in intercropped species, relative to monoculture, is attributable to superior water capture efficiency.

Maitra (2020) asserted that the substantial yields achieved by the intercrops are merely a result of minimal water losses. Furthermore, the water equivalent ratio, a measure that correlates the yield of intercrops to their water utilization, has been documented to be elevated in intercropping systems compared to monoculture. Miao *et al.,* (2016) discovered that actual evapotranspiration, irrigation water utilization, crop transpiration, and groundwater contribution in intercropping systems exceeded those of sole crops, resulting in markedly higher land and water equivalent ratios for intercrops compared to single crops.

Wheat is a crucial grain crop in Egypt, occupying the largest farmed area during the winter season. Nonetheless, a significant disparity exists between production and consumption, with the wheat self-sufficiency ratio of 43%. Intercropping leguminous crops with wheat has been shown to enhance land and water production,

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along with farmer advantages (Ouda *et al*., 2020; Zohry *et al*., 2020). The selection of the legume companion crop and the optimal planting density are crucial for minimizing competition and enhancing complimentary effects to achieve maximum yield benefits for wheat and optimize water utilization. Abou-Keriasha *et al*., (2013) indicated that a faba bean intercropping system with wheat (50% faba bean + 100% wheat at their recommended planting density) resulted in an 8% reduction in wheat output compared to sole wheat cultivation. Hamada and Hamd-Alla (2019) also showed a 3% decrease in wheat yield when intercropped with faba bean (50% faba bean + 100% wheat at their recommended planting density) compared to sole planting yields. These results indicated intense competition between the two intercrops for light and soil nutrients, adversely affecting wheat output. Moreover, the impact of the intercropping system on water use efficiency, particularly under conditions of low water application, was not evaluated.

Several researchers in Egypt implemented intercropping of peas with wheat system. Zohry *et al*. (2020) indicated that intercropping 50% peas with 100% wheat at the specified planting density led to a 5% increase in wheat yield in the second season, relative to sole planting conditions. Conversely, Abd-Rabboh and Koriem (2021) and Sheha *et al*. (2015) established an intercropping system of peas and wheat, with peas planting density of 50% and a wheat planting density of 100%. They determined that wheat yield decreased by less than 1% relative to the yield achieved with sole planting. The diminished yield of wheat in intercropping with peas may be attributed to an inappropriate arrangement of plants, resulting in increased competition for light and soil nutrients. Furthermore, there was no evaluation of the efficacy of water utilization by this intercropping system, particularly during conditions of water scarcity.

A further instance of a legume-cereal intercropping system is the fahl clover intercropping with wheat. Fahl clover is a mono-cut variety of Egyptian clover, characterized by its capacity for stem branching and is harvested only once. Fahl clover is distinguished by its rapid development and substantial forage yield, and it may be planted as either an early short-season winter crop or a full-season winter crop (Bakheit *et al*., 2016). It can also be intercropped with wheat by combining its seeds with those of wheat and sowing them simultaneously. During the harvest, the seeds of both crops are subsequently separated using a sieve (Ali *et al*., 2017). Ali (2018) and El-Shamy *et al*. (2023) intercropped fahl clover at 15%, 25%, and 35% of its recommended planting density with wheat at 100% of its recommended planting density, achieving the best wheat yield with the lowest fahl clover density. The effectiveness of water utilized by the intercropping system was not assessed, especially under conditions of water constraint.

This study was undertaken to examine faba bean, peas, and fahl clover as intercrops with wheat regarding their contributions to enhancing the complementary effect, which positively influences water use efficiency and wheat output. Additionally, to evaluate the impact of imposed water stress on water consumption by these intercropping systems. The aim of this study was to evaluate the impact of three legume co-crops (faba bean, pea, and fahl clover) under three irrigation treatments (100%, 85%, and 70% ETc) on wheat production, land and water equivalent ratios, and farmer profitability.

MATERIALS AND METHODS

This study consists of a two-year field experiment carried out throughout the consecutive seasons of 2021/22 and 2022/23 in El-Minia Governorate, Middle Egypt (28.2847° N, 30.5279° E), focusing on wheat intercropping systems with three legume crops under three irrigation treatments. The experimental region exhibits an arid climate characterized by cold winters and scorching, dry summers (Masoued, 2017) (Figure 1). Data on average daily air temperature, relative humidity, and wind speed for the study seasons were acquired from the weather station situated 320 meters from the experimental area.

The soil of the experimental site is classified as sandy soil. The physical and chemical properties of the soil were determined according to Klute (1986) and Tan (1996) (Tables 1 and 2). The irrigation water was obtained from groundwater, where EC was 0.92 dS/m and pH was 7.53.

Table 1: Main physical properties of soil at the experimental site before cultivation

Soil depth (cm)	Particle size distribution			Texture class	Bulk density (g/cm^3)	Field capacity (%)	Permanent wilting point (%)	Available water (%)
	Sand (%)	Silt (%)	Clay (%)					
0-20	93.4	4.70	2.11	Sandy	1.64	12.8	3.6	9.1
20-40	95.5	3.10	1.50		1.75	11.2	2.9	8.3
40-60	96.1	2.85	0.95		1.69	7.4	2.1	5.3

Table 2: Chemical properties and available macronutrients of the soil at the experimental site before cultivation

Soil depth	pH	ECe	Soluble cations (meq/L)				Soluble anions (meq/L)			
(cm)	(1:2.5)	(dS m^{-1})	Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	CO_3^{-2}	HCO_3^{-}	Cl^{-}	SO_4^{-2}
0-20	7.61	0.690	2.42	1.08	3.12	0.32	-	2.22	3.44	1.28
20-40	7.58	0.692	2.38	1.02	3.12	0.30	-	2.08	3.48	1.26
40-60	7.49	0.686	2.32	1.01	3.10	0.30	-	2.14	3.46	1.13
Available nutrients (mg/kg)										
N				P_20_5				K_20		
12.1				4.61				58.2		

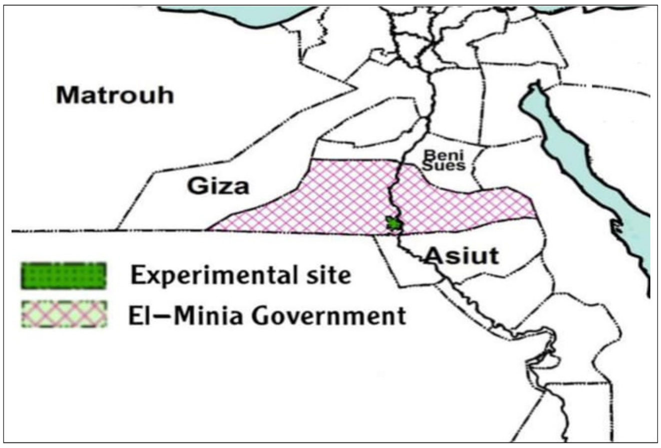

Figure 1: The location of the experimental site at El-Mina Governorate, Egypt

The experimental design employed a split-plot design with three replicates. The treatments comprised the interaction of three irrigation levels with three legume crops intercropped with wheat (*Triticum aestivum L.*), specifically faba bean (*Vicia faba*), peas (*Pisum sativum*), and fahl clover (*Trifolium alexandrinum*), alongside sole wheat and sole legume crops. The irrigation treatments included the required irrigation amount (RI), which constituted 100% of crop evapotranspiration (ETc) and served as the control treatment, alongside two imposed water stress treatments: WS_1, representing 85% ETc, and WS_2, representing 70% ETc. The irrigation treatments were allocated to the main plots, whereas the three intercropping methods were designated to the subplots (Figure 2). The plot space measured 14.4 m² (4.8 x 3.0 m) and included four raised beds, each 1.20 m in width. The prior crop of wheat was sesame in both seasons, sown in May and harvested in early September. Figure 3 illustrates the exclusive cultivation of the three legume crops.

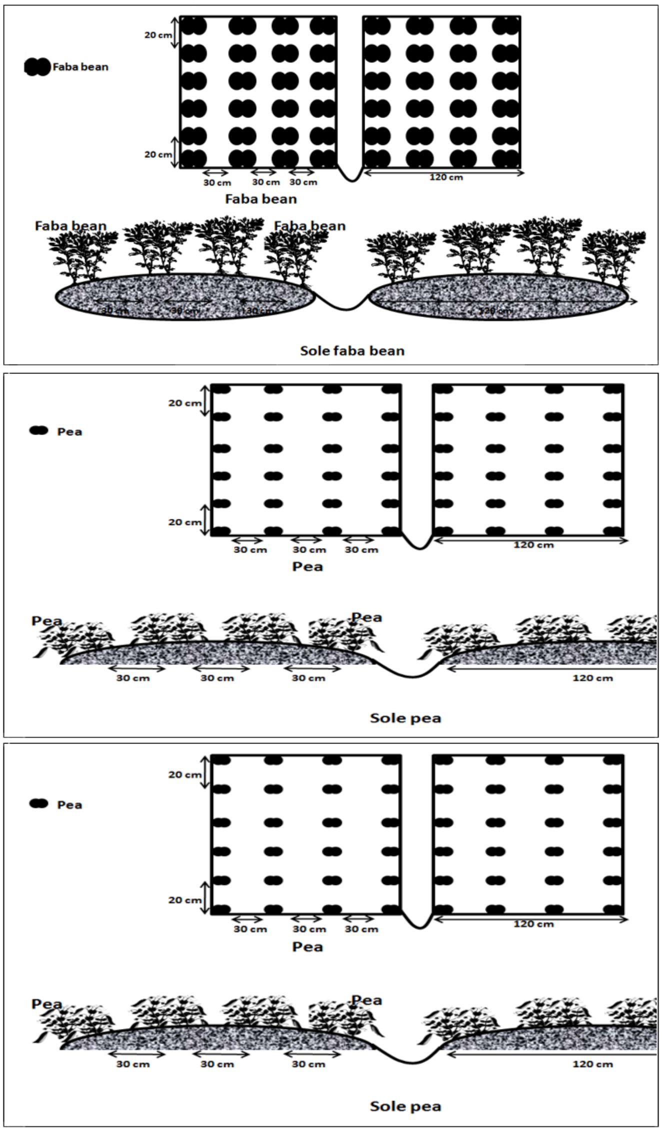

Figure 3: The experimental plots of sole cultivation of the studied legume crops

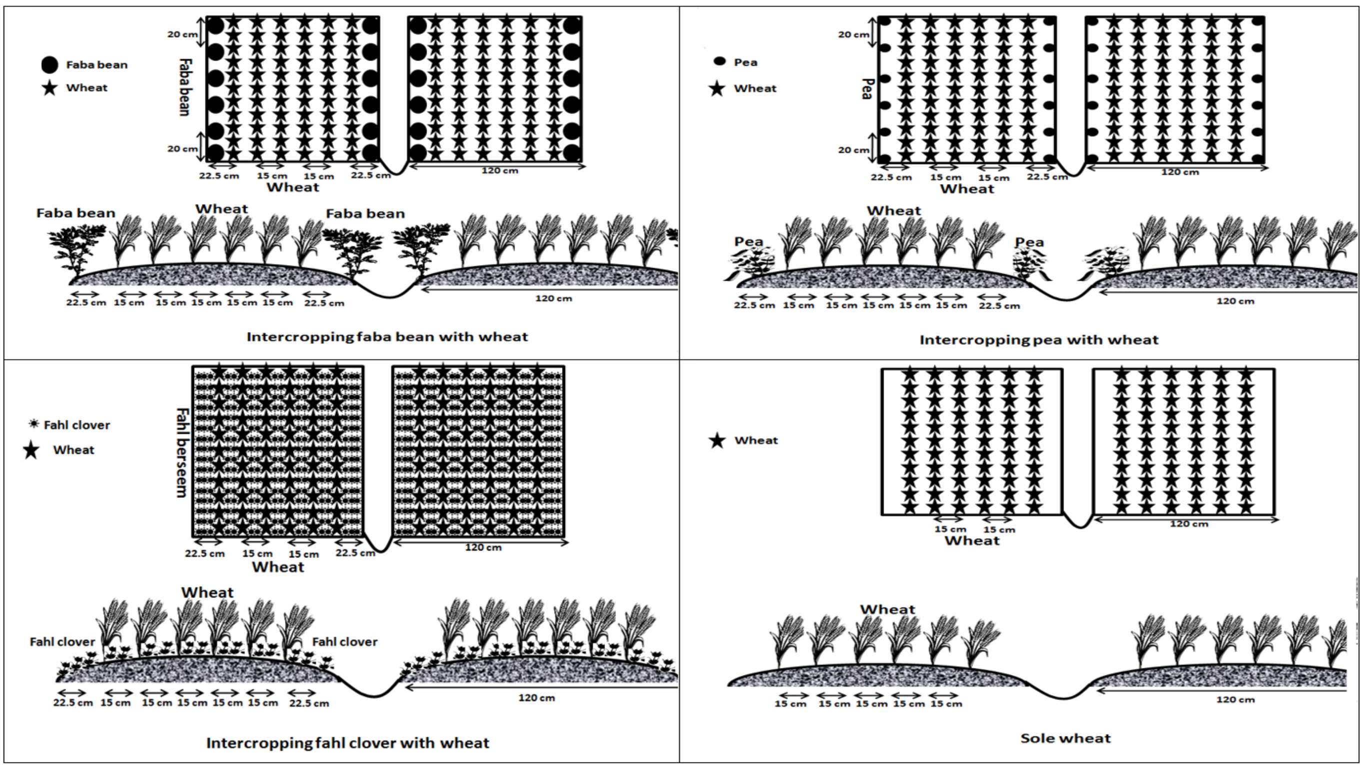

Figure 2: The experimental plots of the wheat cropping systems (intercropped with legume crops and sole wheat)

Monocrop and intercropped wheat

Nitrogen fertilizer was applied to wheat (either as a monocrop or intercropped) at a rate of 537.6 kg N/ha in the form of ammonium nitrate (33.5% N) in five equal increments on days 20, 40, 55, 70, and 85 post-planting. Phosphorus fertilizer was administered as single super phosphate (15.5% P_2O_5) at a rate of 240 kg P_2O_5/ha and was integrated into the soil during land preparation. Potassium was supplied as potassium sulfate (48.8% K_2O) at a rate of 120 kg K_2O/ha during land preparation. The wheat variety Sakha95 was sown on November 18th and 20th during the first and second seasons, respectively, either as a sole crop or intercropped. It was harvested on the 20th and 23rd of April during the first and second seasons, respectively. Wheat seeds were planted in six rows atop the raised beds, with a spacing of 15 cm between each row, according to the full recommended planting density for both sole and intercropped wheat (108.0 kg seed/ha).

Monocrops and intercropped legume crops

Regarding the three legume crops, faba bean and peas were inoculated with *Rhizobium leguminosarum* prior to seeding, while Arabic gum served as a binding agent. The examined cultivars included Giza716, Master B, and fahl respectively for faba bean, peas, and fahl clover, either in monoculture or intercropped systems.

The faba bean was planted on October 21st and 22nd in the first and second seasons, respectively, and harvested on April 15th and 18th in the first and second seasons, respectively (either sole or intercropped). The planting density of faba bean was 25% and 100% (27.0 and 108.0 kg seed/ha) of the recommended density for intercropping and sole cultivation, respectively. Faba bean seeds were intercropped on both sides of the raised beds, with one plant per hill spaced 20 cm apart. Sole faba bean seeds were planted in four rows on the top of raised beds, with a spacing of 30 cm between rows and 20 cm between hills, cultivating two plants per hill. Intercropped and sole faba bean were each administered 12.5 and 50.0 kg N/ha, respectively, in the form of ammonium nitrate (33.5% N) in a single application 10 days post-sowing. The sole faba bean was treated with phosphorus fertilizer, namely single super phosphate (15.5% P_2O_5), at a rate of 600 kg P_2O_5/ha, which was integrated into the soil during field preparation. During land preparation, potassium was supplied as potassium sulfate (48.8% K_2O) at a rate of 120 kg K_2O/ha. The planting dates for peas were October 12th and 14th in the first and second seasons, respectively, with harvests occurring twice when the green pods were market-ready: February 1st and March 28th in the first season, and February 3rd and March 30th in the second season (either sole or intercropped). The planting density of peas was 33% for intercropped and 100% for sole planting, according to the optimum density. Intercropped pea seeds were seeded on both sides of the raised beds, with one plant per hill spaced 20 cm apart. Peas seeds were planted on the top of raised beds in four rows spaced 30 cm apart, with hills positioned 20 cm apart, each containing two plants. Intercropped and sole peas were administered 50.0 and 150.0 kg N/ha, respectively, with ammonium nitrate (33.5% N) in three applications during the first, second, and third irrigation events.

Concerning intercropped fahl clover, 12.0 kg of seeds per hectare (25% of the recommended planting density) were seeded and harvested simultaneously with wheat. Additionally, 48.0 kg of sole fahl clover seeds per hectare were sown in the field on the same day as the wheat and harvested concurrently with the wheat. Nitrogen fertilizer was applied to solitary fahl clover at a rate of 72 kg N/ha of ammonium nitrate (33.5% N) 20 days post-planting, owing to the diminished activity of symbiotic bacteria in the soil. Calcium super phosphate (15.5% P_2O_5) was applied at a rate of 37.2 kg P_2O_5/ha during land preparation.

The estimated irrigation water quantities for crop evapotranspiration or irrigation under standard conditions utilizing a sprinkler system were calculated using the following equation (Allen *et al.,* 1998):

$$ETc = ETo \ x \ kc \quad (1)$$

where ETc = crop evapotranspiration (mm/day), ETo = reference crop evapotranspiration (mm/ day), and kc = crop coefficient.

ETo values were computed utilizing the Penman-Monteith equation (Allen *et al.,* 1998). The kc values for wheat, as reported by Ibrahim *et al.,* (2020), are 0.70, 0.93, 1.15, and 0.33 for the initial, developmental, middle, and end season, respectively, and were utilized to determine the necessary irrigation water depth in accordance with Allen *et al.,* (1998).

The measurements of water consumptive consumption (WCU, mm) were obtained using a time domain reflectometry sensor (TDR). The volumetric soil moisture levels at a depth of 60 cm were measured prior to and following each irrigation session. The seasonal WCU values were computed utilizing the equation established by Israelsen and Hansen (1962) as follows:

$$WCU = \sum_{i=1}^{i=3} \frac{\theta 2 - \theta 1}{100} \times d \quad (2)$$

where i= number of soil layers, θ2= soil moisture content after irrigation, (%, by volume), θ1= soil moisture content just before irrigation, (%, by volume), and d= depth of the soil layer (mm).

The amount of required irrigation water was calculated according to the following equation (Vermeiren and Jopling 1984):

$$\text{AIW} = \frac{\text{ETo} \times \text{I}}{\text{Ea}\ (1 - \text{LR})} \quad (3)$$

where AIW = applied irrigation water depth (mm/day) and Ea = application efficiency equal to 85% for the sprinkler irrigation system. I= interval, Ea= application efficiency, LR = leaching requirements (was not considered). We presumed that the irrigation water supplied to the intercropped wheat suffices to meet the water requirements of its intercropping system with legume crops, given the low planting density of the legume crops.

Irrigation was applied at preset intervals of every three days. The sprinkler system was utilized to implement the designated irrigation strategy. The solid-set sprinkler irrigation system comprised the following components: a pump unit with a capacity of 50 m^3/h and a control head unit; main, submains, and lateral tubes with internal diameters of 150 mm, 110 mm, and 63 mm, respectively; a sprinkler line measuring 18 m in length with a spacing of 6 m between sprinklers; couplers; a sprinkler discharge rate of 1.4 m^3/h at an operating pressure of 3.5 bar (50.8 psi); and additional accessories including valves, bends, plugs, and risers. No precipitation was recorded at the experimental site during either season.

Seed yield for all examined legume crops was determined by harvesting and weighing all plants within the experimental plot area, followed by aggregating the weights of all plots. A comparable technique was executed for wheat plants. The biomass of all examined crops was extracted from the field post-harvest. The experiment was conducted in the same location utilized during the first season in the second season.

Quantification of soil nitrogen

Soil samples were taken prior to planting and post-harvest to ascertain total nitrogen content. Employing a hand-operated auger, twelve cores or tiny samples were randomly extracted within each treatment and repeated. Soil samples were air-dried, softly crushed, and subsequently sieved through a 2 mm mesh to acquire consistent representative samples. Nitrogen was quantified using the micro-Kjeldahl method (Hesse, 1971).

Evaluation of the studied intercropping systems

Land equivalent ratio (LER): LER is an evaluation of the land utilization efficiency of the intercropping system (Rao and Willey, 1980) and it is calculated as follows:

$$LER = \mathrm{LER_A} + \mathrm{LER_B} = \frac{YintA}{YmonoA} + \frac{yintB}{YmonoB} \quad (4)$$

where LER_A and LER_B are the partial land equivalent ratios of crop A and crop B, respectively. $Y_{int,A}$ and $Y_{int,B}$ are the intercropped yields of crop A and crop B, respectively. $Y_{mono,A}$ and $Y_{mono,B}$ are the monoculture yields of crop A and crop B, respectively. If LER > 1, it indicates a higher land utilization efficiency of the intercropping system than that of the monoculture.

Water equivalent ratio (WER): WER quantifies the amount of water that would be needed in single crops to achieve the same yield as produced with one unit of water in intercrops, and it is calculated according to the formula of Mao *et al.*, (2012) as follows:

$$\mathrm{WER} = \left[\frac{\mathrm{Yint},\frac{\mathrm{A}}{\mathrm{WUint}}}{\mathrm{Ymono},\frac{\mathrm{A}}{\mathrm{WUmono}},\mathrm{A}}\right] + \left[\frac{\mathrm{Yint},\frac{\mathrm{B}}{\mathrm{WUint}}}{\mathrm{Ymono},\frac{\mathrm{B}}{\mathrm{WUmono}},\mathrm{B}}\right] \quad (5)$$

where $Y_{int,A}$, $Y_{mono,A}$, $Y_{int,B}$, and $Y_{mono,B}$ are the yields of intercropped crop A, mono crop A, intercropped crop B (legume crop) and mono crop B, respectively. WU_{int}, $WU_{mono,A}$, and $WU_{mono,B}$ are water use by the intercropping system, water use of mono crop A, and water use of intercropped crop B, respectively. If the WER > 1, it suggests that the production of a unit of water is higher than that of the monoculture.

Change in water use (ΔWU)

The ΔWU index (Morris and Garrity, 1993) was employed alongside WER to evaluate the benefits of water use efficiency in intercrops relative to monoculture. ΔWU measures the relative disparity between the observed water intake in the intercrop (WUint,obs) and the anticipated water use derived from the water consumption of the two crop species, adjusted by weights reflecting their proportion in the intercrop (WUint, exp). The anticipated water consumption in intercropping correlates with the water usage of each species in monoculture and the relative yield achieved in intercropping compared to solo cropping (partial LER). Consequently, this formula uses the partial land equivalent ratio of crops A and B as coefficients for ΔWU (Mao *et al.*, 2012) as delineated below:

$$\Delta\mathrm{WU} = [\mathrm{WUint, obs/WUint, exp}] - 1 \quad (6)$$

$$\Delta\mathrm{WU} = [\mathrm{WUint}/(\mathrm{LERint, A \times WUmono, A}) + (\mathrm{LERint, B \times WUmono, B})] - 1 \quad (7)$$

Both WER and ΔWU assess whether a specific intercrop yield (comprising two species) would be attained with increased water (WER > 1; ΔWU < 0) or decreased water (WER < 1; ΔWU > 0) compared to that utilized in sole crops.

Assessment of economic performance

Total income (TI) and monetary advantage index (MAI) were computed to assess the economic benefits of wheat intercropping systems in comparison to sole planting, as per the equation provided by Raza *et al.*, (2021):

Total return (US \$ ha^{-1}) = (yield A x price A) + (yield B x price B) (8)

where A and B represent wheat and the intercropped species, respectively. The prices utilized in the analysis were farm prices as follows: The prices per ton for wheat, faba bean, peas, and fahl clover in the first season were 474, 972, 889, and 2222 USD/ton, respectively, while in the second season, the prices were 430, 605, 806, and 2258 USD/ton, respectively.

Additionally, the monetary advantage index (MAI) was computed based on the LER. It offers explicit insights into the economic benefits of the intercropping system. The MAI was computed as outlined by Ghosh (2004).

MAI= (Value of combined intercrops) * (LER-1)/LER (9)

A positive MAI value indicates the benefits of the intercropping system.

Statistical analysis

All data acquired from the seasonal experiments were analyzed statistically using a split-plot design with three replicates, as per Gomez and Gomez (1964). Least significant differences (LSD) at a 5% probability level were employed for mean comparisons as per Waller and Duncan (1969). The F test was conducted as per Snedecor and Cochran (1989).

RESULTS

Weather conditions at the experimental site

Figure 4a showed that mean temperature was high at both the start and end of the first season, in contrast to the second season. The mean temperature was high in the second season compared to the first for the remainder of the growing season. Moreover, a nearly identical tendency in the fluctuations of relative humidity (Figure 4b) was observed during both seasons. Conversely, significant fluctuations in wind speed values (Figure 4c) were noted in both seasons. Consequently, the ETo values (Figure 4d) were somewhat elevated at the onset and end of the first season, while remaining lower for the most of the season. Accordingly, the value of the required irrigation water and water consumption of the intercropping system is anticipated to be greater in the second season than in the first season.

Irrigation volumes utilized and water consumption of both sole and intercropped crops

Table 3 delineates the anticipated volumes of irrigation water utilized in the examined treatments for both sole wheat and its intercropping systems, in addition to the sole legume crops. The irrigation quantities applied to the sole wheat were identical to those applied to the intercropping systems. The use of water stress treatments, specifically 85% and 70% ETc, led to a 16% and 35% reduction in the irrigation water applied to sole crops and their intercropping systems, respectively, in comparison to the required irrigation volumes. The table indicates that the irrigation water applied to sole peas was the least among the three legume crops examined in both seasons. Moreover, high quantities of irrigation water were utilized in the second season relative to the first season.

Table 4 indicated that the water consumption values for the wheat intercropping systems exceeded those of sole

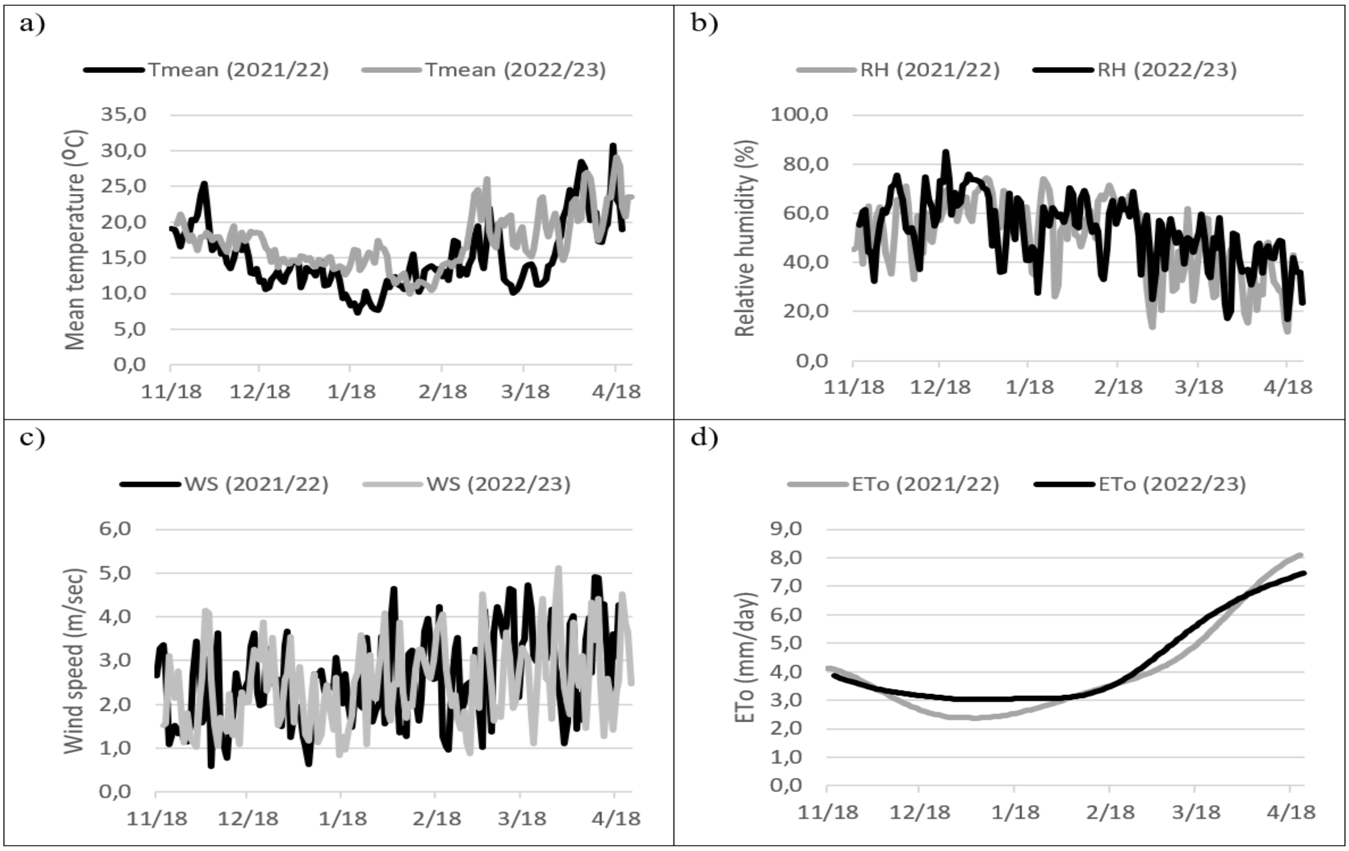

Figure 4: Comparison between average air temperature (MT (a), relative humidity (RH) (b), wind speed (WS) (c) and ETo (d) in the 2021/22 and 2022/23 seasons at the experimental site

Table 3: The amounts of applied irrigation water (mm) to the studied sole crops and their intercropping systems in both seasons

	2021/22 growing season						
	Sole wheat	**Faba bean/wheat**	**Pea/wheat**	**fahl/wheat**	**Sole faba bean**	**Sole pea**	**Sole fahl**
RI	855	855	855	855	842	715	725
WS_1	708	708	708	708	688	586	602
WS_2	559	559	559	559	552	457	483
	2022/23 growing season						
RI	879	879	879	879	918	802	818
WS_1	742	742	742	742	782	668	672
WS_2	576	576	576	576	636	534	546

RI, WS_1, and WS_2= irrigation with 100, 85, and 70% ETc, respectively.

wheat. The faba bean intercropping system exhibited the highest water use among the three wheat intercropping systems due to its greater aboveground biomass compared to the others. The fahl clover intercropping system exhibited the lowest water use across all three irrigation treatments in both seasons. Increased water usage was seen in the second season compared to the first season due to elevated ETo values.

Yields of sole and intercropped wheat under various irrigation regimes

Significant differences were observed between the yield of sole wheat and its yield under the three intercropping systems, as well as the three irrigation treatments (Table 5). These results are consistent over both seasons. The results in table 5 indicated that the intercropping systems of legumes with wheat achieved superior yields compared to sole wheat cropping in both seasons and with the required irrigation applied. In the first season, irrigation at 85% and 70% ETc resulted in the peas intercropping system with wheat achieving greater wheat yield values compared to sole wheat production. In the second season, the yield of intercropped wheat in the three intercropping systems exceeded that of its sole cultivation under both required irrigation and 85% ETc (Table 5).

Yield of sole and intercropped legume crops under different irrigation treatments

Table 6 reveals significant differences between the sole and intercropped faba bean yields under the three irrigation treatments and the interaction between irrigation treatments and cropping systems in both seasons. Furthermore, the F test revealed a significant relationship between the sole and intercropped faba bean yields.

Under the applied water stress treatments, the faba bean yield decreased by 15% for sole faba bean and 21% for intercropped faba bean when irrigated at 85% ETc, averaged over two seasons, in comparison to the yields

Table 4: Water consumptive use (mm) of the studied sole crops and their intercropping systems in both seasons

	2021/22 growing season						
	Sole wheat	Faba bean/wheat	Peas/wheat	fahl/wheat	Sole faba bean	Sole pea	Sole fahl
RI	727	807	799	785	716	608	616
WS_1	606	678	672	660	597	507	513
WS_2	484	543	543	528	477	405	411
	2022/23 growing season						
RI	747	822	814	807	798	681	696
WS_1	623	691	685	679	665	568	580
WS_2	498	553	548	543	532	454	464

RI, WS_1, and WS_2= irrigation with 100, 85, and 70% ETc, respectively.

Table 5: The sole and intercropped wheat yields (ton/ha) under different intercropping systems (CS) and irrigation treatments (IR) in both seasons

Cropping system	2021/22 growing season				2022/23 growing season			
	RI	WS_1	WS_2	Mean	RI	WS_1	WS_2	Mean
Sole wheat	6.27	5.62	5.09	5.66^{ab}	6.26	5.64	5.48	5.79^{b}
Intercropped faba bean with wheat	6.57	5.52	5.00	5.69^{a}	6.65	5.87	5.36	5.96^{ab}
Intercropped peas with wheat	6.82	5.81	5.24	5.96^{a}	6.87	6.11	5.40	6.13^{a}
Intercropped fahl with wheat	6.28	5.17	4.65	5.34^{b}	6.67	5.87	5.31	5.95^{ab}
Mean	6.48^{a}	5.53^{b}	4.99^{c}	5.66	6.60^{a}	5.87^{b}	5.39^{c}	5.96
$LSD_{0.05}$								
IR	0.36				0.37			
CS	0.31				0.33			
IR X CS	NS				NS			

Means that do not share the same letters in a column differ significantly at $p < 0.05$ using least significant differences (LSD), calculated separately for each year; NS= Nonsignificant, RI, WS_1, and WS_2= irrigation with 100, 85, and 70% ETc, respectively.

Table 6: The yield of faba bean (ton/ha) under different cropping systems (CS), and irrigation treatments (IR) in both seasons

Cropping system	2021/22 growing season				2022/23 growing season			
	RI	WS_1	WS_2	Mean	RI	WS_1	WS_2	Mean
Sole faba bean	3.74	3.20	2.90	3.24^{a}	3.72	3.20	3.05	3.33^{a}
Intercropped faba bean	0.97	0.80	0.70	0.81^{b}	0.97	0.80	0.73	0.83^{b}
Mean	2.35^{a}	1.97^{b}	1.77^{b}		2.34^{a}	1.99^{b}	1.89^{b}	
	$LSD_{0.05}$	F test			$LSD_{0.05}$	F test		
IR	0.31	--			0.21	--		
CS	--	**			**	**		
IR X CS	0.35				0.22			

Means that do not share the same letters in a column differ significantly at $p < 0.05$ using least significant differences (LSD), calculated separately for each year; RI, WS_1, and WS_2= irrigation with 100, 85, and 70% ETc, respectively.

achieved under optimal irrigation conditions. The production losses for faba bean were 19% for sole cultivation and 27% for intercropped cultivation under irrigation at 70% ETc, averaged over the two seasons, compared to the values achieved under optimal irrigation (Table 6).

Similar trends were found for peas (Table 7), where a significant difference between the yield of sole and intercropped peas were found under the three irrigation treatments in both seasons. Furthermore, a significant relationship between the yield of the sole and intercropped peas.

The yield reduction of sole and intercropped peas under irrigation at 85% ETc was respectively 12% and 23%, averaged over two seasons, in comparison to their values under optimal irrigation conditions. Under irrigation at 70% ETc, the production losses for sole and intercropped peas were respectively 13 and 26%, averaged over two seasons, compared to the yields obtained with adequate irrigation (Table 7).

Regarding fahl clover, a significant difference between the sole and intercropped yields under the three irrigation treatments was found in both seasons. In addition, the F test revealed a significant relationship between the yield of the sole and intercropped fahl clover (Table 8).

The reduction in the sole and intercropped fahl clover yields under irrigation with 85% ETc was respectively 13 and 24%, averaged over the two seasons, compared to its values obtained under the required irrigation. However, under irrigation with 70% ETc, the reductions in the yield of fahl clover were 14 and 29% for sole and intercropped fahl clover, respectively, averaged over the two seasons, compared to its values obtained under the required irrigation (Table 8).

Available soil N contents under the sole wheat and its intercropping systems

The effect of the sole wheat and its intercropping systems, as well as irrigation treatments, on soil available N is presented in Table 9. The results revealed significant differences between the values of N under the studied intercropping systems and irrigation treatments in both seasons and the interaction between them in the second season. The values of soil available N were higher under all wheat intercropping systems compared to the values under sole wheat irrigated with the three irrigation treatments. The highest values of soil available N were found when faba bean was intercropped with wheat, and the lowest values were obtained when fahl clover was intercropped with wheat under the three irrigation treatments. Furthermore, the values of soil available N were reduced under both water stress treatments (Table 9).

Table 7: The yield of peas (ton/ha) under different cropping systems (CS), and irrigation treatments (IR) in both seasons

Cropping system	2021/22 growing season				2022/23 growing season			
	RI	WS_1	WS_2	Mean	RI	WS_1	WS_2	Mean
Sole peas	8.50	7.40	6.50	7.46^a	8.36	7.40	6.55	7.46^a
Intercropped peas	2.34	2.10	1.70	2.05^b	2.38	2.10	1.75	2.08^b
Mean	5.42^a	4.74^{ab}	4.10^b		5.37^a	4.76^b	4.15^b	
	$LSD_{0.05}$	F test			$LSD_{0.05}$	F test		
IR	0.90	--			0.26	--		
CS	--	**			**	**		
IR X CS	NS				NS			

Table 8: The yield of clover (ton/ha) under different cropping systems (CS), irrigation treatments (IR) in both seasons

Cropping system	2021/22 growing season				2022/23 growing season			
	RI	WS_1	WS_2	Mean	RI	WS_1	WS_2	Mean
Sole fahl clover	0.79	0.70	0.60	0.69^a	0.79	0.74	0.67	0.73^a
Intercropped fahl clover	0.26	0.20	0.20	0.22^b	0.23	0.20	0.18	0.20^b
Mean	0.52^a	0.45^b	0.39^b		0.53^a	0.47^{ab}	0.40^b	
	$LSD_{0.05}$	F test			$LSD_{0.05}$	F test		
IR	0.06	--			0.09	--		
CS	--	**			**	**		
IR X CS	NS				NS			

Table 9: Available soil N (mg/kg), as affected by sole wheat, its intercropping systems (IS) and irrigation treatments (IR) in both growing seasons

Cropping systems	2021/22 growing season				2022/23 growing season			
	RI	WS_1	WS_2	Mean	RI	WS_1	WS_2	Mean
Sole wheat	11.5	10.1	9.09	10.2$_c$	12.1	10.2	9.15	10.5^b
Faba bean/wheat	14.5	12.9	11.0	12.8^a	14.6	13.2	11.5	13.1^a
Peas/wheat	13.4	11.9	10.4	11.9^b	13.9	12.2	10.9	12.3^a
Fahl clover/wheat	12.3	10.4	9.48	10.7^c	12.5	10.7	9.87	11.0^b
Mean	12.9^a	11.3^b	9.98^c		13.3^a	11.6^b	10.3^c	
$LSD_{0.05}$								
IR	0.65				0.87			
IS	0.86				1.18			
IR X IS	NS				1.69			

Means that do not share the same letters in a column differ significantly at $p < 0.05$ using least significant differences (LSD), calculated separately for each year; NS= Nonsignificant, RI, WS_1 and WS_2= irrigation with 100, 85, and 70% ETc, respectively.

Land equivalent ratio (LER)

In the first season, the values of LER_{legume} in Table 10 revealed significant differences between wheat intercropping systems for intercropping systems and interaction between irrigation treatments and intercropping systems. The values of LER_{wheat} revealed significant differences between wheat intercropping systems for intercropping systems only. Whereas, the values of LER_{total} showed significant differences between wheat intercropping systems for irrigation treatments, intercropping systems and their interaction. In the second season, the values of LER_{legume} revealed significant differences between wheat intercropping systems for intercropping systems and interaction between irrigation treatments and intercropping systems. Whereas, the values of LER_{total} showed significant differences between wheat intercropping systems for intercropping systems only (Table 10).

Table 10 also showed that the values of partial LER for fahl clover were the highest of the three legume crops under their intercropping system with wheat and under the three irrigation treatments. Furthermore, the highest values of partial LER for wheat and total LER were found under peas intercropping system with wheat under the three irrigation treatments in both seasons (Table 10).

Water equivalent ratio (WER) and change in water use (ΔWU)

The values of WER_{legume} in Table 11 revealed significant differences between wheat intercropping systems in

Table 10: The land equivalent ratios as affected by wheat intercropping systems (IS) under the studied irrigation treatments (IR) in both seasons

Irrigation treatments	Intercropping system	2021/22 growing season			2022/23 growing season		
		LER_{legume}	LER_{wheat}	LER_{total}	LER_{legume}	LER_{wheat}	LER_{total}
RI	Faba bean/wheat	0.26	1.04	1.31	0.26	1.06	1.32
	Peas/wheat	0.27	1.09	1.36	0.29	1.10	1.39
	Fahl/wheat	0.33	0.99	1.32	0.30	1.06	1.36
	Mean	0.28^{a}	1.04^{a}	1.33^{a}	0.28^{a}	1.07^{a}	1.35^{a}
WS_1	Faba bean/wheat	0.25	0.98	1.23	0.25	1.04	1.29
	Peas/wheat	0.28	1.03	1.32	0.28	1.08	1.37
	Fahl/wheat	0.32	0.92	1.24	0.27	1.04	1.31
	Mean	0.28^{a}	0.98^{a}	1.26^{ab}	0.27^{a}	1.05^{a}	1.32^{a}
WS_2	Faba bean/wheat	0.24	0.98	1.23	0.24	0.98	1.22
	Peas/wheat	0.27	1.03	1.30	0.27	0.98	1.25
	Fahl/wheat	0.32	0.91	1.23	0.27	0.97	1.24
	Mean	0.28^{a}	0.97^{a}	1.25^{b}	0.26^{a}	0.98^{a}	1.24^{a}
Mean (IS)	Faba bean/wheat	0.25^{b}	1.00^{a}	1.25^{b}	0.24^{c}	1.03^{a}	1.27^{b}
	Peas/wheat	0.27^{b}	1.05^{a}	1.32^{a}	0.28^{b}	1.05^{a}	1.33^{a}
	Fahl/wheat	0.32^{a}	0.94^{b}	1.26^{ab}	0.33^{a}	1.02^{a}	1.30^{a}
$LSD_{0.05}$							
IR		NS	NS	0.07	NS	NS	NS
IS		0.04	0.05	0.06	0.03	NS	0.05
IR X IS		0.06	NS	0.10	0.05	NS	NS

Table 11: Water equivalent ratio (WER) and change in water use (ΔWU) of wheat intercropping systems (IS) under the studied irrigation treatments (IR) in both seasons

IR	IS	2021/22 growing season				2022/23 growing season			
		WER_{legume}	WER_{wheat}	WER_{total}	ΔWU (%)	WER_{legume}	WER_{wheat}	WER_{total}	ΔWU (%)
RI	F/wheat	0.23	0.94	1.17	-14.3	0.25	0.97	1.22	-17.7
	P/wheat	0.21	0.99	1.20	-16.4	0.25	1.01	1.26	-20.5
	F/wheat	0.26	0.92	1.17	-14.9	0.24	0.99	1.23	-19.0
	Mean	0.23^{a}	0.95^{a}	1.18^{a}	-15.2^{b}	0.25^{a}	0.99^{a}	1.24^{a}	-19.1^{b}
WS_1	F/wheat	0.22	0.88	1.10	-8.71	0.24	0.94	1.18	-15.1
	P/wheat	0.21	0.93	1.15	-12.2	0.24	0.99	1.23	-17.9
	F/wheat	0.25	0.85	1.10	-8.49	0.23	0.95	1.18	-15.2
	Mean	0.23^{a}	0.89^{b}	1.12^{b}	-9.8^{a}	0.24^{a}	0.95^{b}	1.19^{a}	-16.1^{ab}
WS_2	F/wheat	0.21	0.86	1.09	-7.84	0.23	0.88	1.11	-10.2
	P/wheat	0.20	0.92	1.12	-10.7	0.23	0.90	1.14	-10.6
	F/wheat	0.25	0.84	1.08	-7.75	0.22	0.89	1.11	-10.3
	Mean	0.22^{a}	0.97^{b}	1.10^{b}	-8.78^{b}	0.23^{a}	0.89^{c}	1.12^{b}	-10.4^{a}
Mean (IS)	F/wheat	0.21^{b}	0.90^{b}	1.12^{b}	-15.2^{a}	0.24^{a}	0.93^{b}	1.17^{a}	-19.5^{a}
	P/wheat	0.21^{b}	0.94^{a}	1.16^{a}	-9.81^{b}	0.24^{a}	0.96^{a}	1.20^{a}	-17.2^{b}
	F/wheat	0.25^{a}	0.87^{b}	1.12^{b}	-8.77^{b}	0.24^{a}	0.94^{ab}	1.18^{a}	-11.4^{c}
$LSD_{0.05}$									
IR		NS	0.04	0.05	2.67	NS	0.02	0.04	2.28
IS		0.02	0.03	0.02	2.53	NS	0.03	NS	0.49
IR X IS		NS	NS	NS	NS	NS	0.04	NS	NS

Means that do not share the same letters in a column differ significantly at $p < 0.05$ using least significant differences (LSD), calculated separately for each year; NS= Nonsignificant, RI, WS_1, and WS_2= irrigation with 100, 85, and 70% ETc, respectively.

the first season only. The values of WER_{wheat} revealed significant differences between irrigation treatments and wheat intercropping systems in the first season and between irrigation treatments, wheat intercropping systems and the interaction between them in the second season. Furthermore, the values of WER_{total} showed significant differences between wheat intercropping systems for irrigation treatments, and intercropping systems in the first season. In the second season, the values of WER_{legume} revealed significant differences between wheat intercropping systems for irrigation treatments only (Table 11).

Under the required irrigation, the highest values of legume partial WER were found for fahl clover in both seasons. The highest values of WER_{wheat} and total WER were found for the peas intercropping system in both seasons. Application of the water stress treatments resulted in lower values of partial and total WER, where the peas intercropping system attained total WER value under irrigation with WS_1 in the second seasons higher than total WER obtained by the faba bean intercropping system under the application of the required irrigation (Table 11).

Furthermore, significant differences between the value of ΔWU for wheat intercropping systems, and irrigation treatments in both seasons were found. The three intercropping systems attained values of WER > 1 and ΔWU < 0, which reflect an increase in the efficiency of the water use (Table 11).

Total income (TI) and monetary advantage index (MAI)

The results in Table 12 revealed higher values of TI for all the studied intercropping systems, compared to wheat monoculture, with the highest values attained by peas intercropping system with wheat under the three irrigation treatments in both seasons.

Similarly, higher positive valued of MAI were attained under the three studied intercropping systems, which reflected definite yield and economic advantages over the mono cultivation of wheat. In particular, MAI was the highest for peas intercropping system with wheat than the other studied intercropping systems, which implies the most advantageous economic mixture (Table 12).

DISCUSSION

Yield of intercropped wheat exceeded that of its monoculture under required irrigation

Our findings indicated an enhancement in the yield of intercropped wheat within the examined legume intercropping systems, relative to its yield under sole cropping across both seasons, given the implementation of required irrigation and water stress treatments, with the exception of WS_2 in the second season (Table 5). Reports indicate that intercropping with legumes gives significantly better outputs compared to monoculture (Yu *et al.*, 2016). Moreover, legume crops possess the capacity to fix nitrogen in their roots via rhizobium through the process of symbiotic nitrogen fixation (Pelzer *et al.*, 2012), hence promoting the benefits of intercropping with legumes, specifically the complementing utilization of nitrogen sources by the intercrops (Dhima *et al.*, 2014).

Moreover, the yield of intercropped wheat in the second season surpassed that of the first season, attributable to the residual effects of legume crops, as noted by Banik *et al.*, (2018), who reported a significant presence of residual nitrogen in the soil following legume cultivation, thereby enhancing soil fertility. Kirihetti (2018) noted that a quantity of fixed nitrogen was returned to the soil as crop residue following the cultivation of legumes. Mat Hassan *et al.*, (2012) revealed that legumes mobilize phosphorus in the soil throughout their growth, enhancing phosphorus uptake in subsequent cereal crops.

The peak intercropped wheat production was achieved when peas were intercropped with wheat in both seasons, as well as the faba bean intercropping system (Table 5). While earlier studies in Egypt reported a decline in wheat production when intercropped with peas (Abd-Rabboh and Koriem 2021; Sheha *et al.*, 2015), our findings demonstrated an increase in wheat output attributable to the reduced planting density of peas in our investigation. Intercropping peas with cereals enhances production stability by belowground nutrient transfer via direct root contact, diffusion of exudates, and mycorrhizal associations (Garcia *et al.*, 2016). Oelbermann *et al.* (2015) assert that intercropping influences rhizodeposition and soil microbial characteristics, which con-

Table 12: Total income (TI) and monetary advantage index (MAI) of the studied wheat intercropping systems under different irrigation treatments in both seasons

	RI		WS_1		WS_2	
	TI (USD/ha)	MAI	TI (USD/ha)	MAI	TI (USD/ha)	MAI
	2021/22 growing season					
Sole wheat	2,972	--	2,664	--	2,413	--
Faba bean/wheat	4,058	960	3,152	589	3,051	570
Peas/wheat	5,313	1,406	4,366	1,058	3,995	922
Fahl clover/wheat	3,517	853	2,668	516	2,649	495
	2022/23 growing season					
Sole wheat	2,692	--	2,426	--	2,357	--
Faba bean/wheat	3,447	836	3,267	734	2,747	495
Peas/wheat	4,874	1,342	4,590	1,240	3,734	747
Fahl clover/wheat	3,478	921	3,234	765	2,713	525

tribute to yield benefits. Moreover, peas exhibit a defined growth pattern, flowering and maturing sooner than wheat cultivars, with nitrogen being released from nodules post-flowering, coinciding with the nitrogen need during the grain filling stage of wheat (Bioland, 2021). Additionally, peas can provide ground cover among wheat plants, thereby inhibiting weed growth (Daryanto *et al*., 2020). Naudin *et al*., (2010) assert that interspecific competition for soil nitrogen between wheat and peas is less significant than intraspecific competition among wheat plants in monoculture, with wheat yields frequently demonstrating superiority in intercropping relative to sole cropping. Furthermore, Jensen *et al.*, (2020) demonstrated that intercropping peas with wheat effectively diminished nitrogen fertilization requirements and production costs, while maintaining output with reduced mineral nitrogen pollution.

While prior studies in Egypt indicated reductions in wheat yield within its intercropping system with faba bean (Abou-Keriasha *et al*., 2013, Hamada and Hamd-Alla 2019), our findings demonstrated an enhancement in intercropped wheat yield due to minimal competition between faba bean and wheat plants, as the faba bean planting density in our investigation was 25%, in contrast to 50% in the earlier studies. The low planting density of faba bean may promote synergistic interaction between the two intercrops and diminish competition. Moreover, Benincasa *et al*., (2012) demonstrated that in the intercropping system of wheat and faba bean, each species experienced competitive effects from its companion, with faba bean prevailing when present in greater proportions than wheat. Xue *et al*., (2016) reported that carboxylate concentrations in the faba bean rhizosphere were 10 to 20 times higher than those in wheat within the intercropping system, indicating a substantial capacity for soil phosphorus mobilization and improved phosphorus uptake by wheat, aided by faba bean. Chapagain and Riseman (2014) demonstrated that intercropping wheat with faba bean enhanced wheat biomass and grain protein content relative to monoculture wheat cultivation.

Our findings indicated that the yield of intercropped wheat with fahl clover was the lowest among the three intercropping systems, likely due to significant interspecific competition between the two crops. Pellegrini *et al*., (2021) observed diminished wheat production when it was temporarily intercropped with clover, attributable to elevated interspecific competition. Fahl clover, being a leguminous crop capable of symbiotic nitrogen fixation in its root nodules, enhances soil nitrogen availability, resulting in a modest increase in intercropped wheat yield during the first season and higher value in the second season. Abou-Kerisha *et al.,* (2008), Abou-Kerisha *et al*., (2013), and Ali (2018) reported analogous findings, indicating an enhancement in wheat production when intercropped with fahl clover at a low seeding rate of fahl clover. Andersen *et al*., (2007) asserted that the enhanced early growth capacity and extensive lateral root systems of legumes may be critical determinants of their competitive prowess for soil resources. Due to fahl clover being sown on the same day as wheat, it may forfeit the benefits gained by faba beans and peas, which were planted subsequently to wheat within their intercropping system. Yu *et al*., (2016) posited that species sown earlier will generally exhibit superior individual performance compared to those sown later in intercropping systems due to size-asymmetric competition. Variations in sowing dates across intercropped species are expected to provide earlier-planted crops with preferential access to soil resources relative to those sown later (Yu *et al*., 2016).

Intercropping peas and faba beans with wheat mitigates yield losses under imposed water stress

In the first season, with irrigation at 85% and 70% ETc, only the intercropping system of peas with wheat achieved a greater yield of intercropped wheat compared to sole wheat agriculture (Table 5). Prudent *et al*., (2016) indicate that peas plants exhibit tolerance to mild drought conditions, since their roots face reduced competition for water during periods of low water availability. In the second season, the yield of intercropped wheat in the three intercropping systems exceeded its sole production under irrigation and 85% ETc, with the maximum yield recorded in the intercropping system with peas (Table 5). Reports indicate that peas contribute residual nitrogen to the soil at a rate of 50-60 kg/ha (Kanwar, 1990), potentially enhancing wheat development and increasing its resilience to water stress within an intercropping system. Daryanto *et al.,* (2020) discovered that in a peas-wheat intercropping system, moisture levels in shallower soil were lower than those in deeper soil compared to monocultures. Peas can provide ground cover between wheat plants, so lowering soil temperature and evaporation, and consequently minimizing water loss from the soil surface. Whereas, Khan *et al*., (2010) assert that faba bean has more sensitivity to terminal and temporary drought compared to other temperate grain legumes, suggesting it may have competed more with wheat for water than peas during conditions of water stress.

Mixed legume-cereal stands reportedly exhibit reduced evaporation owing to a more intricate canopy structure, resulting in enhanced drought tolerance (Tsubo and Walker, 2004). Certain characteristics that affect stand and canopy structure in intercropping systems can more effectively manage or diminish humidity, consequently lowering disease prevalence (Ma *et al*., 2019). Moreover, Gregory (1988) indicated that the roots system of legumes continued to expand near maturity, but the root system growth of cereal crops halted post-anthesis. As a result, underground competition for nutrients and water diminished following the anthesis of cereal crops.

Imposed water stress diminished both sole and intercropped legume crops

The decline in yield of the intercropped legume species under imposed water stress treatments (Tables 6, 7, and 8) was minimal for peas, followed by faba bean and fahl clover. The production decreases of intercropped crops under imposed water stress exceeded those observed in sole cultivation. These higher yield losses are due to the applied irrigation water being based on the needs of wheat, which may not be ideal for legume crops under imposed water stress. Furthermore, higher competition between the roots of legume crops and the roots of wheat for the limited water supply existed due to its higher planting density, which gives a higher advantage to wheat roots in water acquisition than the intercropped crops. Similar trends were reported for legume-sugar beet intercropping system by Ouda and Zohry (2023).

Soil N content increased under peas and faba bean intercropping system with wheat

Our results indicated that irrigation with the required amount attained higher values of soil available N under the three wheat intercropping systems than the value obtained for sole wheat cultivation (Table 9). It has been reported that intercropping with legumes enhances soil N through plant residues (Amossé *et al*., 2014). Moreover, the values of soil available N were higher in the second season than in the first season due to the decomposition of legume crop residues that benefit the subsequent crop (Arcand *et al*., 2014). The highest values of soil available N were found when faba bean was intercropped with wheat due to its ability to fix higher values of N than peas and fahl clover (Carranca *et al*., 1999) and to its dense rooting systems (Shanmugam *et al*., 2022). Bargaza *et al*. (2015) proposed that intercropping with faba bean enables its roots to penetrate deeper soil layers, thereby accessing a greater soil volume (Belachew *et al*., 2019), which may contribute to increased organic matter decomposition in the soil (Arcand *et al*., 2014) compared to peas and fahl clover.

It has been reported that faba bean has the highest reliance on N_2 fixation for growth in comparison with peas, which leads to high N credit for the following crops (Hauggaard-Nielsen *et al*., 2009). Faba bean has been shown to attain higher amounts of N derived from the atmosphere, than peas. In addition, faba bean can reduce NO_3-N leaching by scavenging residual soil NO_3-N, higher than pea (Peoples *et al*., 2009).

The results also showed high value of available soil nitrogen contents when peas were intercropped with wheat in both seasons (Table 9). According to the findings of Rodriguez *et al*., (2020), the residual organic matter of this system, which is proportionally richer in nitrogen compared to monocropping, can help to replenish the soil's mineral reserves and, thus, preserve its natural fertility. It has been reported that a 17% increase in soil organic matter was found when peas was intercropped with wheat compared to sole wheat cultivation (Abbady *et al.,* 2016). Whereas, Zohry *et al*., (2020) noted an 11% rise in soil organic matter with the same intercropping system relative to sole wheat. Carlsson *et al*., (2017) reported that, in peas intercropping system with wheat, wheat is more competitive in its use of mineral nitrogen, urges peas to fix more atmospheric N by symbiosis to meet its needs, which hinders the development of weeds due to the lack of nitrogen resources. Furthermore, an increase in soil nitrogen content was observed when fahl clover was intercropped with wheat (Table 9), compared to the value found after sole wheat cultivation. Similar results were obtained by Ouda and Zohry (2024), Ali (2018), and Abdel-Zaher *et al*. (2009).

Under imposed water stress treatments, available soil N was reduced under all wheat intercropping systems, compared to its values when required irrigation was applied (Table 9). According to Latati *et al*., (2016), intercropping has a facilitative function in mitigating stressful conditions through plant root interactions and mobilizing limited or unavailable nutrients, such as phosphorus in harsh environmental conditions. Barzana *et al*., (2021) reported reduction of the nutrient availability for plants under lower soil water availability, which in turn limits their nutrient uptake and assimilation. However, intercropping the three legume crops with wheat contributed to increase available soil N under water stress treatments, compared to the values obtained under sole wheat cropping, with the highest values obtained under faba bean intercropping system with wheat (Table 9). Furthermore, Bargaza *et al*., (2015) indicated that intercropping of faba bean with wheat under low water availability promotes faba bean nodulation and root growth in deeper soil layers.

Intercropping systems of peas and faba beans with wheat achieved a superior land equivalent ratio (LER)

The results in Table 10 indicated LER_{wheat} values exceeding 1.0, attributable to elevated intercropped wheat yields compared to monoculture yields across both seasons and the three irrigation treatments, with the highest value recorded for the peas intercropping system, followed by the faba bean intercropping system. This research indicated that peas were marginally more effective than faba bean in enhancing the growth conditions of wheat within their intercropping system, and both outperformed fahl clover, which also exhibited an increase in land use efficiency, as noted by Brintha and Seran (2009). Moreover, these findings demonstrated that the effects of complementarity and collaboration among these legumes were more pronounced than those of competition, as noted by Justes *et al*. (2021). The peak values of LER_{wheat} in the peas intercropping system indicate a greater compatibility between the two intercrops than that observed in the faba bean and fahl clover intercropping systems. Additionally, the complementarity in the utilization of natural resources, stemming from diminished interspecies competition and niche partitioning (Gitari *et al*., 2020), may also be a contributing factor. An LER value exceeding 1.0 signifies that interspecific facilitation surpasses interspecific competition, suggesting that intercropping enhances land use efficiency (Machiani *et al*., 2018). Lithourgidis *et al.,* (2011) indicated that LER values exceeding 1.0 suggest that a monocropping system necessitates more acreage to achieve equivalent yields as an intercropping system. Chapagain and Riseman (2014) demonstrated that intercropping wheat with faba bean achieved a superior land equivalent ratio due to enhanced total land outputs, greater land productivity, and improved wheat biomass, in contrast to monoculture wheat agriculture.

It is noteworthy that under WS_1, the values of LER_{wheat} remained over 1.0 owing to the enhancement in wheat yield attributed to the residual effects of legume crops in the soil. The application of WS_2 decreased the LER_{wheat} values below 1.0, hence lowering the LER_{total} values in the second season.

The LER values obtained in this study were consistent with those previously documented in Egypt. Abd-Rabboh and Koriem (2021) recorded a greater LER value for the intercropping system of peas with wheat (50% of its planting density) in the second season compared to the first, specifically 1.56 versus 1.45, respectively. Zohry *et al.,* (2020) reported LER values of 1.33 and 1.40 for the same intercropping system in the first and second seasons, respectively. Regarding the faba bean intercropping system with wheat, Hamada and Hamd-Alla (2019) observed a LER of 1.33 and Abdel-Wahab and El Manzlawy (2016) reported a LER value of 1.24. Furthermore, Ali (2018) reported a LER value of 1.25 for the intercropping of fahl clover with wheat and Ouda and Zohry (2024) achieved a LER value of 1.28.

The intercropping system of peas and faba bean with wheat enhances water use efficiency

Our findings indicated that the irrigation water applied to each wheat intercropping system was equivalent to that applied to sole wheat. Consequently, two crops utilized the irrigation water allocated to wheat plants, indicating the efficient utilization of applied irrigation water within intercropping systems. Moreover, water usage in wheat intercropping systems with legumes exceeded that of sole wheat (Table 4). The water absorption is attributed to two species: wheat and the legume companion crop. These results are corroborated by the findings of Morris and Garrity (1993) and Mao *et al.,* (2012). Moreover, Yin *et al.,* (2019) indicated that the daily soil evaporation of intercrops was inferior to that of sole cropping, demonstrating a notable benefit of intercrops in enhancing crop water availability. Our findings indicated that the water consumption in wheat intercropping systems did not merely reflect the sum of the water usage of individual crops; rather, it was lower than the total water consumption value. Yin *et al.,* (2018) elucidated this conclusion by the synergistic use of irrigation water throughout the season in irrigated regions. Furthermore, Yang *et al.*, (2011) asserted that intercropping represents the most effective and sustainable approach for enhancing water utilization in agricultural production by augmenting soil moisture and reducing runoff, thereby leading to increased yields and serving as a strategy for water conservation (Chen *et al.,* 2018).

The optimal planting density of the companion crop is crucial in influencing growth characteristics. In our experiment, the employed plant density for each legume crop was optimal for augmenting water utilization by the intercrops and yielding elevated values of WER_{legume} (Table 11). Wang *et al.,* (2018) demonstrated that optimal planting density enhanced photosynthesis and the microclimate between the two intercrops, hence boosting root length density and root absorption area.

Moreover, our findings demonstrated the fahl clover's superior water efficiency relative to the other legumes examined, achieving the highest partial WER during the first season across all three irrigation regimens. Nonetheless, the values of WER_{wheat} and WER_{total} exceeded 1.0, with the highest observed in the intercropping system with peas during both seasons across all three irrigation treatments, indicating that intercropping with leguminous crops enhanced the water utilization of wheat under both non-stressful and stressful conditions. Intercropping peas with wheat has been shown to utilize water resources more efficiently and can be employed in arid situations to achieve higher yields (Pankou *et al.,* 2021). The elevated WER_{total} achieved due to the residual impact of peas on the soil in the second season enhanced soil water retention, which favorably influenced the yield of intercropped wheat. Intercropping significantly improves water use efficiency, influenced by the sowing ratio of the intercropping system, demonstrating a substantial water usage advantage (Mao *et al.,* 2012). Furthermore, intercropping with legumes enhances soil properties, including the augmentation of soil aggregate stability (Rücknagel *et al.,* 2016) and improvements in water retention and infiltration (Wick *et al.,* 2017), which positively influences the yield of intercropped wheat.

Both WER and ΔWU were employed to assess the efficiency of irrigation water utilization in intercropping compared to monoculture. Moreover, the values of WER > 1 and ΔWU < 0 indicated that the legume-wheat intercropping systems significantly improved water use efficiency, demonstrating a substantial water usage advantage with the required irrigation application. Under the applied water stress treatments, the recorded WER values for peas exceeded those of the faba bean and fahl clover intercropping systems, while the ΔWU value was below 0.0, which suggest enhanced water use efficiency (Table 11). Reports indicate that intercropping can improve water use efficiency by 4% to 99% relative to sole crops, particularly when water availability is not constrained (Stomph *et al.,* 2020; Mao *et al.,* 2012; Tan *et al.,* 2020). The root system significantly contributes to water acquisition in intercrops, as species mixes have been demonstrated to enhance root length density, resulting in reduced water loss via evaporation (Pankou *et al.,* 2021). Ouda and Zohry (2024) reported WER values for fahl clover intercropping systems with wheat in Egypt as 0.25, 1.00, and 1.25 for WER_{fahl}, WER_{wheat}, and WER_{total}, respectively.

The intercropping system of peas and faba beans with wheat achieved greater total income and monetary advantage index

The results demonstrated that the total income (TI) values of the three intercropping systems surpassed those derived from sole wheat cultivation across the three irrigation treatments in both seasons, with the highest value achieved from the peas-wheat intercropping system. Correspondingly, the monetary advantage index (MAI) values were maximized in the peas-wheat intercropping system across all three irrigation regimes for both seasons. The findings align with those of LER, where Dhima *et al.,* (2007) indicated that the highest LER values in an intercropping system result in economic advantages reflected in MAI values. The results can be attributed to increased overall productivity in intercropping with comparatively lower input investment (Banik *et al.,* 2006).

CONCLUSION

The rising demand for agroecosystems that integrate high crop output with diminished input levels necessitates the implementation of legume-cereal intercropping systems. Our findings indicate that intercropping the three legume species with wheat is a potential strategy for enhancing land and water use efficiency via improved light capture and complementing nutrient and water uptake. Our findings indicate that intercropping is advantageous, both with required irrigation and under conditions of induced water scarcity. The notable yield advantage of wheat compared to its sole cultivation resulted from enhanced land utilization and improved exploitation of environmental resources for plant growth. Moreover, these intercropping systems exhibit elevated productivity and might be adopted by farmers due to their yield benefits. The analysis of the three intercropping systems demonstrated that the peas-wheat intercropping system is the most beneficial, achieving the maximum land equivalent ratio, water equivalent ratio, total income , and monetary advantage index under both required irrigation and 80% ETc water stress conditions. This suggests that, in the context of limited water resources, intercropping wheat with legumes, particularly peas, is advisable to enhance the utilization of existing water resources.

REFERENCES

Abbady K.A., El-Maaz E.I.M., Ahmed H.M.R.M., Zohry A.A. (2016). Carbon sequestration as a function of intercropping management practices and different nitrogenous fertilizer types. *Journal of Soil Science and Agriculture Engineering*, 7: 565- 586.

Abdel-Wahab T.I., El-Manzlawy A.M. (2016). Yield and quality of intercropped wheat with faba bean under different wheat plant densities and slow–release nitrogen fertilizer rates in sandy soil. *American Journal of Experimental Agriculture*, 11: 1-22.

Abdel-Zaher Sh. R., Abdel-Galil M.A., Ibrahim S.T. (2009). Effect of seeding rates of fahl berseem mixed with wheat under three rates of nitrogen fertilizer on yield and yield components of both crops. *J. Agric. Sci.*, 34: 6653 – 6666.

Abd-Rabboh A.M.K, Koriem M.H.M. (2021). Increasing unit area productivity and net income by intercropping peas with some wheat cultivars under different levels of nitrogen fertilizer. *Journal of the Advances in Agricultural Researches*, 27: 260-275.

Abou-Keriasha M.A., Eisa N. M.A., Lamlom M.M. (2013). Benefits of legume crops in rotation and intercropping for increased production and land use. *Egypt. J. Agron.,* 35:183-197.

Abou-Kerisha M.A., Gadallah R.A., Badr M.M.A. (2008). Effect of preceding and intercropping crops on yield and yield components of wheat. *Minufiya J. Agric. Res.,* 33: 709-728.

Ali A.M. (2018). Effect of Intercropping Egyptian Clover Variety Fahl with Wheat on Yield and Its Components Under Some Agricultural Treatments. PhD thesis. *Assuit University*, Egypt.

Ali A.M., Shalaby E.M., Ali E.A., Ibrahim S.T. (2017). Impact of intercropping Egyptian clover (*Trifolium Alexandrinum var fahl*) with wheat on water use efficiency of irrigation. *Journal of Applied Life Sciences International*, 14: 1-12.

Allen R.G, Pereira L.S, Raes D., Smith M. (1998). *Crop evapotranspiration: Guideline for computing crop water requirements*. FAO No56, pp 109-158.

Amossé C., Jeuffroy M.H., Mary B., David C. (2014). Contribution of relay intercropping with legume cover crops on nitrogen dynamics in organic grain systems. *Nutrients Cycling in Agroecosystems*, 98: 1– 14.

Andersen M.K., Hauggaard-Nielsen H, Weiner J., Jensen E.S. (2007). Competitive dynamics in two-and three-component intercrops. *Journal of Applied Ecology*, 44: 545-551.

Arcand M.M., Lemke R., Farrell R.E., Knight J.D. (2014). Nitrogen supply from belowground residues of lentil and wheat to a subsequent wheat crop. *Biology and Fertility of Soils*, 50: 507-515.

Bakheit B.R., Abo-Elwafa A., Abdel-Galil M.M., Abdelmonem A.M.A. (2016). Impacts of recurrent selection and synthetic population on forage and seed yields of mono-cut Egyptian clover (*Trifolium alexandrinum L.*). *Assiut J. Agric. Sci*., 47: 31-44.

Banik D., Upadhyay H., Devi B. P., Darvhankar M. (2018). Effect of different irrigation system on growth and development of wheat-chickpea intercropping. *Bull. Env. Pharmacol. Life Sci*., 8: 32-34.

Banik, P., Midya A., Sarkar B.K., Ghose S.S. (2006). Wheat and chickpea intercropping systems in an additive series experiment: Advantages and weed smothering. *European Journal of Agronomy*, 24: 325–332.

Bargaza, A, Isaacb M.E., Jensena E. S., Carlsson G. (2015). Intercropping of faba bean with wheat under low water availability promotes faba bean nodulation and root growth in deeper soil layers. *Procedia Environmental Sciences*, 29: 111–112.

Barzana G., Rios J. J., Lopez-Zaplana A., Nicolas-Espinosa J., Yepes-Molina L., Garcia-Ibañez P., *et al.* (2021). Interrelations of nutrient and water transporters in plants under abiotic stress. *Physiol. Plantarum*, 171: 595–619.

Bedoussac L., Journet E-P., Hauggaard-Nielsen H., Naudin C., Corre-Hellou G., Jensen E.S., Prieur L., Justes E. (2015). Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming: A review. *Agron Sustain Dev.,* 35: 911–935.

Belachew K.Y., Nagel K.A., Poorter H., Stoddard F.L. (2019). Association of shoot and root responses to water deficit in young faba bean (*Vicia faba L.*) plants. *Frontier in Plant Science*,10:1063.

Benincasa P., Pace R., Tosti G., Tei F. (2012). Early interspecific interference in the wheat/faba bean (*Triticum Aestivum/ Vicia Faba ssp*), minor and rapeseed/squarrosum clover (*Brasslca Napus* var. Oleifera/*Trifolium Squarrosum*) intercrops. *Italian Journal of Agronomy*, 7: e24.

Bioland (2021). *Bioland und Demeter Z-Saatgut für die Herbstaussaat 2021.* Esslingen: Bioland-Handelsgesellschaft.

Brintha I., Seran T.H. (2009). Effect of paired row planting of radish (*Raphanus sativus* L.) intercropped with vegetable amaranths (*Amaranths tricolor L.*) on yield components in sandy regosol. *Journal of Agricultural Science*, 4: 19-28.

Carlsson G., Bedoussac L., Cupina B., Djordjevic V., Gaudio N., Jensen E.-S., Jeuffroy M.-H., Journet E.-P., Justes E., Mikic A. (2017). Does a Mixture of Pea Varieties with Different Leaf Morphology Improve Crop Performance?. *In Proceedings of the International Conference on Advances in Grain Legume Cultivation and Use*, Novi Sad, Serbia, 27–28 September 2017.

Carranca C., de Varennes A., Rolston D. (1999). Biological nitrogen fixation by faba bean, pea and chickpea, under field conditions, estimated by the N^{15} isotope dilution technique. *European Journal of Agronomy*, 10: 49-56.

Chai Q., Gan Y., Zhao C., Xu H., Waskom R. M, Niu Y., Siddique K.H.M. (2016). Regulated deficit irrigation for crop production under drought stress. A review. *Agron. Sustain. Dev.*, 36: 2-21.

Chapagain T., Riseman A. (2014). Intercropping wheat and beans: Effects on agronomic performance and land productivity. *Crop Science,* 54: 2285-2293.

Chen G.X., Kong Y., Gan R., Zhang F., Feng A., Yu C., Zhao S., Wan Q.C. (2018). Enhancing the systems productivity and water use efficiency through coordinated soil water sharing and compensation in strip intercropping. *Sci. Rep.*, 8: 10494.

Cisneros J.B.E., Oki T., Arnell N.W., Benito G., Cogley J.G., Döll P., Jiang T., Mwakalila S.S. (2014). *Fresh Water Resources. In Climate Change: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Field C.B., Barros V.R., Dokken D.J., Mach K.J., Mastrandrea M.D., Bilir T.E., Chatterjee M., Ebi K.L., Estrada Y.O., Genova R.C., *et al*. Eds.; Cambridge University Press: Cambridge, UK and New York, NY, USA, pp. 229–269.

Coll L., Cerrudo A., Rizzalli R., Monzon J.P., Andrade F.H. (2012). Capture and use of water and radiation in summer intercrops in the south-east Pampas of Argentina. *Field Crops Res.*, 134: 105–113.

Daryanto S., Fu B., Zhao W., Wang, S., Jacinthe, P.-A., Wang, L. (2020). Ecosystem service provision of grain legume and cereal intercropping in Africa. *Agric. Syst.,* 178: 102761.

Dhima K.V., Vasilakoglou I.B., Keco R.Xh., Dima A.K., Paschalidis K.A., Gatsis T.D. (2014). Forage yield and competition indices of faba bean intercropped with oat. *Grass and Forage Science*, 69: 376–383.

Dhima K.V., Lithourgidis A.A., Vasilakoglou I.B., Dordas C.A. (2007). Competition indices of common vetch and cereal intercrops in two seeding ratios. *Field Crops Research*, 100: 249-256.

Ditzler L., van Apeldoorn D.F., Pellegrini F., Antichi D., Bàrberi P., Rossing W.A.H. (2021). Current research on the ecosystem service potential of legume inclusive cropping systems in Europe: A review. *Agronomy for Sustainable Development*, 41: 26.

El-Shamy M. A., EL-Mansoury M. A. M. Kasem A. A. (2023). Effect of different sowing dates under intercropping patterns for fahl berseem and wheat crop under the north middle Nile Delta region. *Middle East Journal of Applied Sciences*, 13: 130-142.

Forouzani M., Karami E. (2011). Agricultural water poverty index and sustainability. *Agron Sustain Dev.*, 31: 415–432.

Gan Y., Siddique K.H.M., Turner N.C., Li X.-G., Niu J.-Y., Yang C., Liu L., Chai Q. (2013). Ridge-furrow mulching systems—an innovative technique for boosting crop productivity in semiarid rain-fed environments. *Adv Agron.,* 118: 429–476.

Garcia K., Doidy J., Zimmermann S. D., Wipf D., Courty P. E. (2016). Take a trip through the plant and fungal transportome of mycorrhiza. *Trends Plant Sci.,* 21: 937–950.

Ghosh P.K. (2004). Growth, yield, competition and economics of groundnut/cereal fodder intercropping systems in the semi-arid tropics of India. *Field Crops Research*, 88: 227-237.

Gitari H. I., Nyawade S. O., Kamau S. Karanja N., Gachene N., Raza M. A., *et al.* (2020). Revisiting intercropping indices with respect to potato-legume intercropping systems. *Field Crops Research*, 258: 107957.

Gomez, K.A.; Gomez A.A. (1984). *Statistical Procedures for Agricultural Research*. 2nd ed. John Wiley and Sons, Inc. New York. pp 22-67.

Gregory P. J. (1988). *Root Growth of Chickpea, Faba Bean, Lentil, and Pea and effects of water and salt stresses. In: R. I. Summerfield (ed.). World Crops: Cool Season Food Legumes*. Kluwer Academic Publishers.

Hamada A., Hamd-Alla W. (2019). Productivity of intercropped wheat with faba bean under crop sequences and foliar application of humic acid. *Egyptian Journal of Agronomy*, 41: 225-241.

Hauggaard-Nielsen H., Mundus S., Jensen E.S. (2009). Nitrogen dynamics following grain legumes and subsequent catch crops and the effects on succeeding cereal crops. *Nutr. Cycl. Agroecosyst.*, 84: 281–291.

Hesse P. R. A. (1971). *Text Book of Soil Chemical Analysis*. Juan Murry (Publisher) Ltd., London. 1971. pp 27-45.

Hu F., Chai, Q., Yu A., Yin W., Cui H., Gan Y. (2015) Less carbon emissions of wheat–maize intercropping under reduced tillage in arid areas. *Agron. Sustain. Dev.*, 35: 701–711.

Ibrahim, M.M., Abd El Fattah N.G., Abd El-Mageed H.N. (2020). Net irrigation water requirements for wheat in egypt under climate change conditions. *Journal of Soil Sciences and Agricultural Engineering*, 11: 385-393.

IPCC (2013). *Summary for Policymakers*. *In*: *Climate Change. The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Stocker T. F., Qin D., Plattner G. K., Tignor M., Allen S. K., Boschung J., Nauels A., Xia Y., Bex V., Midgley P. M., Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Israelsen O.W., Hansen V.E. (1962). *Irrigation Principles and Practices*. 3rd Edition, Wiley International Edition, New York.

Ivanov S., Fedorova E.E., Limpens E., De Mita S., Genre A., Bonfante P., *et al.* (2012). Rhizobium–legume symbiosis shares an exocytotic pathway required for arbuscule formation. *Proc. Natl. Acad. Sci.*, 109: 8316–8321.

Justes E, Bedoussac L., Dordas C., Frak E., Louarn G., Boudsocq S., Journet E.P., Lithourgidis, A., Pankou C., Zhang C., *et al.* (2021). The 4C approach as a way to understand species interactions determining intercropping productivity. *FASE*, *8*, 3.

Kanwar, J.S. (1990). Punjab Veg. *Grower*, 25: 12-15.

Khan H.R., Paull J.G., Siddique K.H.M., Stoddard F. L. (2010). Faba bean breeding for drought-affected environments: A physiological and agronomic perspective. *Field Crops Research*, 115: 279–286.

Kirihetti D. (2018). *Direct Assessment of the Fixation and Release of Nitrogen by Pea, Lentil, Chickpea and Faba Bean.* A Master of Science Thesis. University of Saskatchewan Saskatoon, Canada.

Klute A. (1986). *Methods of Soil Analysis, Part I. Physical and Mineralogical Method*. American Society of Agronomy. 1986. Madison. Wisconsin. USA.

Koskey G., Leoni F., Carlesi S., Avio L., Bàrberi P. (2022). Exploiting plant functional diversity in durum wheat–lentil relay intercropping to stabilize crop yields under contrasting climatic conditions. *Agronomy*, 12: 210.

Latati M., Bargaz A., Belarbi B., Lazali M., Benlahrech S., Tellah S., Kaci G., Drevon J.J., Ounane S.M. (2016). The intercropping common bean with maize improves the rhizobial efficiency, resource use and grain yield under low phosphorus availability. *Eur. J. Agron.*, 72: 80–90.

Lithourgidis A.S., Vlachostergios D.N., Dordas C.A., Damalas C.A. (2011). Dry matter yield, nitrogen content, and competition in pea-cereal intercropping systems. *Eur. J. Agron.*, 34: 287–294.

Ma L.K., Dong K., Zhu J.H., Dong, Y. (2019). Effects of N application on faba bean chocolate spot and canopy microclimate in wheat and faba bean intercropping system. *The Journal of Applied Ecology*, 30: 951–960.

Machiani M.A., Javanmard A. Morshedloo M.R., Maggi F. (2018). Evaluation of competition, essential oil quality and quantity of peppermint intercropped with soybean. *Industrial crops and products*, 111: 743-754.

Maitra S., Shankar T., Banerjee P. (2020). *Potential and advantages of maize-legume intercropping system, In: Maize Production and Use*, ed A. Hossain (Intechopen).

Mao L.L., Zhang L.Z., Li W.W., Werf W.V.D., Sun J.H., Spiertz H., and Li L. (2012). Yield advantage and water saving in maize/pea intercrop. *Field Crops Research*, 138: 11-20.

Masoued S. R. (2017). *Climate and its Impact on Diseases in the Northern Upper Egypt (Applied Climatology Study). Msc Thesis.* Department of Geography, Cairo University, Egypt. pp. 15-36.

Mat Hassan H., Marschner P., McNeill A., Tang C. (2012). Grain legume pre-crops and their residues affect the growth, P uptake and size of P pools in the rhizosphere of the following wheat. *Biol. Fertil. Soils*, 48: 775–785.

Miao Q., Rosa R.D., Shi H., Paredes P., Zhu L., Dai J., Gonçalves J.M., Pereira L.S. (2016). Modeling water use, transpiration and soil evaporation of spring wheat–maize and spring wheat–sunflower relay intercropping using the dual crop coefficient approach. *Agri. Wat. Manag*., 165: 211-229.

Morris R.A, Garrity D.P. (1993). Resource capture and utilization in intercropping: Water. *Field Crops Research*, 34: 303–317.

Naudin C., Corre-Hellou G., Crozat S.P.Y., Jeuffroy M. (2010). The effect of various dynamics of N availability on winter pea–wheat intercrops: Crop growth, N partitioning and symbiotic N_2 fixation. *Field Crops Research*, 119: 2-11.

Oelbermann M., Regehr A., Echarte L. (2015). Changes in soil characteristics after six seasons of cereal–legume intercropping in the Southern Pampa. *Geoderma Reg.,* 4: 100–107.

Ouda S. and Zohry A. (2023). Increasing sustainability by intercropping legume crops with sugar beet under imposed water stress. *Irrigation and Drainage*, 1–26.

Ouda S., Zohry A., Abdel-Wahab S. (2020). Sustainable intensive cropping to reduce irrigation-induced erosion: II. Changing cropping sequence under sprinkler irrigation practice. *Moroccan Journal of Agricultural Science*. 1(1):26-33.

Ouda S., Zohry A. (2024). *Increasing Land and Water Use Efficiencies of Wheat: Case Study of Egypt. In: Integration of Legume Crops with Cereal Crops under Changing Climate: Sustainably Increases Food Production*. Springer Publishing House.

Pankou C., Lithourgidis A., Dordas C. (2021). Effect of irrigation on intercropping systems of wheat (*Triticum aestivum* L.) with Pea (*Pisum sativum* L.). *Agronomy*, 11: 283.

Pellegrini F., Carlesi S., Nardi G., Bàrberi P. (2021). Wheat–clover temporary intercropping under Mediterranean conditions affects wheat biomass, plant nitrogen dynamics and grain quality. *Eur. J. Agron*., 130: 126347.

Pelzer E., Bazot M., Makowski D., Corre-Hellou G., Naudin C., Al Rifai M., Baranger E., Bedoussac L., Biarnes V., Boucheny P., Carrouée B., Dorvillez D., Foissy D., Gaillard B., Guichard L., Mansard M.-C., Omon B., Prieur L., Yvergniaux M., Justes E., Jeuffroy M.H. (2012). Pea-wheat intercrops in low input conditions combine high economic performances and low environmental impacts. *European Journal of Agronomy*, 40: 39–53.

Peoples M.B., Brockwell J., Herridge D.F., Rochester I.J., Alves B.J.R., Urquiaga S., Boddey R.M., Dakora F.D., Bhattarai S., Maskey S.L., *et al*. (2009). The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. *Symbiosis*, 48: 1–17.

Prudent M., Vernoud V., Girodet S., Salon C. (2016). How nitrogen fixation is modulated in response to different water availability levels and during recovery: A structural and functional study at the whole plant level. *Plant and Soil*, 399: 1–12.

Qin A.Z, Huang G.B., Chai Q., Yu A.Z, Huang P. (2013). Grain yield and soil respiratory response to intercropping systems on arid land. *Field Crops Res*., 144: 1–10.

Rahman T., Liu X., Hussain S., Ahmed S., Chen G., Yang F. (2017). Water use efficiency and evapotranspiration in maize-soybean relay strip intercrop systems as affected by planting geometries. *PLoS ONE*, 12: e0178332.

Rao M.R., Willey R.W. (1980). Evaluation of yield stability in intercropping: studies on sorghum/pigeon pea. *Experimental Agriculture*, 16: 105-116.

Raza M.A., Gul H., Wang J., Shehryar Y.H., Qin R., Bin Khalid M.H. *et al.* (2021). Land productivity and water use efficiency of maize-soybean strip intercropping systems in semi-arid areas: A case study in Punjab Province Pakistan. *Journal of Cleaner Production*, 308: 127282.

Rodriguez C., Carlsson G., Englund J.-E., Flöhr A., Pelzer E., Jeuffroy M.-H., Makowski D., Jensen E.S. (2020). Grain Legume-Cereal Intercropping Enhances the Use of Soil-Derived and Biologically Fixed Nitrogen in Temperate Agroecosystems. A Meta-Analysis. *Eur. J. Agron*., 118: 126077.

Rücknagel J., Götze P., Koblenz B., Bachmann N., Löbner S., Lindner S., Bischoff J., Christen O. (2016). Impact on soil physical properties of using large-grain legumes for catch crop cultivation under different tillage conditions. *European Journal of Agronomy*, 77: 28–37.

Shanmugam S., Hefner M., Pelck J.S., Labouriau R., Kristensen, H.L. (2022). Complementary resource use in intercropped faba bean and cabbage by increased root growth and nitrogen use in organic production. *Soil Use and Management*, 38: 729–740.

Sheha A.M., Abdel-Wahab T.I., Abdel-Wahab S.I. (2015). Maximizing nitrogen and land use efficiencies of intercropped wheat with pea under different pea sowing dates. *Journal of Plant Sciences*, 3: 358-371.

Snedecor G.W., Cochran, W.G. (1989). *Statistical Methods*, 8th Edition, Iowa State University Press.

Stomph T., Dordas C., Baranger A., de Rijk J., Dong B., Evers J., Gu C., Li L., Simon J., Jensen, E.S., *et al*. (2020). Designing intercrops for high yield, yield stability and efficient use of resources: Are there principles? *Adv. Agron*., 160: 1–50.

Tan M.X., Gou F., Stomph T.J., Wang J., Yin W., Zhang L.Z., Chai Q., Van der Werf W. (2020). Dynamic process-based modelling of crop growth and competitive water extraction in relay strip intercropping: model development and application to wheat– maize intercropping. *Field Crops Research*, 246: 107613.

Tan K.H. (1996). *Soil Sampling, Preparation and Analysis*. Marcel Dekker, Inc. New York. p. 391.

Tosti G., Falcinelli B., Guiducci M. (2023) Lentil–cereal intercropping in a Mediterranean area: Yield, pests and weeds. *Agronomy Journal*, 115: 2570–2578.

Tsubo M., Walker S. (2004). Shade effects on *Phaseolus vulgaris L.* intercropped with *Zea mays L.* under well-watered conditions. *Journal of Agronomy and Crop Science*, 190: 168–176.

Vermeiren L., Jopling G.A. (1984). *Localized irrigation*. FAO Irrigation and Drainage paper No. 36, Rome, Italy.

Waller R.A., Duncan D.B. (1969). *Bays Rule for the Symmetric Multiple Comparison Problem*. American State Association. USA.

Wang Y.F., Qin Y.Z., Chai Q., Feng F.X., Zhao C., Yu, A.Z. (2018). Interspecies interactions in relation to root distribution across the rooting profile in wheat-maize intercropping under different plant densities. *Frontiers in Plant Science*, 9: 483-489.

Wick A., Berti M., Lawley Y., Liebig M. (2017). *Integration of Annual and Perennial Cover Crops for Improving Soil Health. In: Soil Health and Intensification of Agroecosytems*; Elsevier BV: Amsterdam, The Netherlands, pp. 127–150.

Xue Y., Xia H., Christie P., Zhang Z., Li L., Tang C. (2016). Crop acquisition of phosphorus, iron, and zinc from the soil in cereal/legume intercropping systems: a critical review. *Annals of Botany*, 117: 363–377.

Yang C., Huang G., Chai Q., Luo Z. (2011). Water use and yield of wheat/maize intercropping under alternate irrigation in the oasis field of northwest China. *Field Crop Res.,* 124: 426–432.

Yin W., Yu A.Z., Guo Y., Wang Y.F., Zhao C., Fan Z.L., Hu F.L., Chai Q. (2018). Straw retention and plastic mulching enhance water use via synergistic regulation of water competition and compensation in wheat-maize intercropping systems. *Field Crops Research*, 229: 78-94.

Yin W., Fan Z.L., Hu F.L., Fan H., Yu A.Z., Zhao C., Chai Q. (2019). Straw and plastic mulching enhances crop productivity via optimizing interspecific interactions of wheat–maize intercropping in arid areas. *Crop Sci*., 59, 2201-2213.

Yu Y., Stomph T.-J., Makowski D., Zhang L., van der Werf W. (2016). A Meta-analysis of relative crop yields in cereal/legume mixtures suggests options for management. *Field Crop Res*., 198: 269–279.

Zohry A., Ouda S., Abdel-Wahab T. (2020). Sustainable intensive cropping to reduce irrigation-induced erosion: Intercropping systems under surface irrigation practice. Moroccan Journal of Agricultural Science. *Moroccan Journal of Agricultural Science*, 1: 63-71.