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Sustainable intensification of maize (Zea mays L.) systems under water stress through cowpea (Vigna unguiculata L.) intercropping in Egypt

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Abstract

Water scarcity and declining soil fertility pose major challenges to maize production in arid regions such as Egypt. This study evaluated cowpea–maize intercropping as a strategy for sustainable intensification under water stress conditions. A two-year field experiment was conducted to assess the effects of three irrigation regimes (120%, 100%, and 80% of crop evapotranspiration, ETc) and three cowpea planting dates (two weeks before, simultaneous with, and two weeks after maize) on crop productivity, soil fertility, resource-use efficiency, and economic returns. The results showed that intercropping significantly improved system performance compared to monocropping. Intercropped maize yields increased in the second season due to the residual effects of cowpea, while soil organic matter, nitrogen, and phosphorus were consistently higher in intercropping systems. Although water stress reduced yields, intercropping maintained higher productivity and resource-use efficiency under both moderate and severe stress conditions. Land equivalent ratio and water equivalent ratio values exceeded unity across all treatments, indicating superior land and water-use efficiency. In addition, intercropping systems achieved higher total income and positive monetary advantage index, confirming their economic viability. These findings highlight the potential of legume-based intercropping as a climate-resilient and resource-efficient strategy for sustainable intensification of maize systems in arid environments.

1. Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops globally, with production exceeding 1.2 billion metric tons (FAOSTAT, 2025). It plays a central role in global food systems as a staple for human consumption and a key component of animal feed, while also serving as a raw material for various industrial products such as starch, sweeteners, and bioethanol. In Egypt, maize represents the principal summer cereal crop and occupies the largest summer cultivated area; however, domestic production meets only about 47% of national demand, creating a substantial food security gap (Ouda et al., 2020).

Addressing this gap requires not only increasing productivity but also improving the sustainability of maize-based systems under conditions of limited water resources and climate variability. Conventional intensification strategies—such as improved irrigation management, optimized fertilization, and the development of high-yielding hybrids—have contributed to yield gains and enhanced resource-use efficiency (Gomaa et al., 2021; Mansour, 2025). However, these approaches alone may not be sufficient to ensure long-term sustainability, particularly under increasing water scarcity and environmental constraints. Therefore, there is growing interest in sustainable intensification strategies that enhance productivity while conserving resources and maintaining ecosystem functions. Sustainable intensification seeks to enhance agricultural outputs while preserving or improving ecosystem services through the strategic management of biological interactions and ecological processes (Jhariya et al. 2021).

Intercropping cereals with legumes is widely recognized as a key pathway toward sustainable intensification. This practice improves system productivity through complementary resource use, enhances soil fertility via biological nitrogen fixation, and increases resilience to environmental stresses (Sánchez-Navarro et al., 2019). Cowpea (*Vigna unguiculata* L.) is a suitable legume for such systems due to its moderate drought tolerance, rapid growth, and adaptability to shaded conditions (Boukar et al., 2013). Cowpea can fix between 36 and 75 kg N ha^{-1} (Vasconcelos et al., 2020), contributing to improved soil nitrogen availability, while also enhancing soil organic matter through rhizodeposition and residue incorporation (Sánchez-Navarro et al., 2019). In addition, root exudates from cowpea can stimulate soil microbial activity and improve phosphorus availability, thereby supporting nutrient cycling and soil health (Amorim et al., 2022).

Intercropping systems, defined as the simultaneous cultivation of two or more crops on the same land area (Kumar et al., 2020), where multiple sustainability benefits are offered beyond yield improvement. In maize-based systems, cowpea intercropping has been shown to enhance soil carbon sequestration (Arshad, 2025), improve rhizosphere nutrient dynamics (Latati et al., 2014), and increase soil moisture retention compared with monocropping (Dube et al., 2014). Moreover, the complementary canopy structure of cowpea and maize can improve microclimatic conditions by reducing soil evaporation and moderating canopy temperature, thereby enhancing crop performance under water stress (Ouda and Zohry, 2024). These combined effects contribute to improved resource-use efficiency and system resilience, which are central components of sustainable agricultural systems.

Despite these advantages, research on cowpea–maize intercropping in Egypt has largely focused on yield optimization and land-use efficiency through variations in planting geometry and fertilization practices (Elsaid et al., 2019; El-Ghobashy et al., 2018, 2020; El-Shamy et al., 2022; Salama et al., 2022; Shehata and Hamd-Alla, 2023). Limited attention has been given to the integrated effects of planting time and water stress on system performance. Only a few studies have evaluated the role of cowpea planting dates (Abou-Keriasha et al., 2011; El-Shamy et al., 2021), and even fewer have examined the interaction between intercropping and water stress conditions (Taha

and Kasem, 2022). Consequently, there is a lack of comprehensive understanding of how these factors jointly influence productivity, soil fertility, and resource-use efficiency within a sustainability framework.

Therefore, this study aimed to evaluate the potential of cowpea–maize intercropping as a strategy for sustainable intensification under water stress conditions in arid Egypt. Specifically, the study investigated the interactive effects of cowpea planting dates and irrigation regimes on (i) crop productivity, (ii) soil fertility indicators, (iii) land and water-use efficiency, and (iv) economic performance. By integrating these components, the study provides a comprehensive assessment of how intercropping can enhance resilience under limited water availability.

2. Materials and methods

2.1. Experimental Site and Climate Conditions

A two-year field experiment was conducted during the 2022 and 2023 growing seasons in El-Minia Governorate, Middle Egypt (28.05° N, 30.44° E; 40 m a.s.l.), under a drip irrigation system. The region is characterized by an arid climate with mild winters and hot, dry summers (Masoued, 2017) (Fig. 1). Meteorological data, including daily air temperature, relative humidity, and wind speed, were obtained from a weather station located approximately 320 m from the experimental site.

2.2. Soil Characteristics and Source of Irrigation Water

The experimental soil was classified as sandy with low organic matter content (0.31%). Soil physical and chemical properties were determined prior to cultivation following standard procedures (Klute, 1986; Tan, 1996) (Tables 1 and 2). Irrigation water was sourced from groundwater, with an electrical conductivity of 0.92 dS m^{-1} and pH of 7.53.

Table 1
Primary physical characteristics of soil at the experimental location prior to 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	93.40	4.70	2.11	Sandy	1.64	12.76	3.61	9.15
20–40	95.50	3.10	1.50		1.75	11.22	2.89	8.33
40–60	96.10	2.85	0.95		1.69	7.43	2.09	5.34

Table 2
Chemical characteristics and accessible macronutrients of the soil at the experimental location prior to 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_2O_5				K_2O		
12.14				4.61				58.21		

2.3. Experimental Design and Treatments

The experiment was arranged in a split-plot design with three replicates. Irrigation treatments were assigned to main plots, while cropping systems were allocated to subplots. Treatments consisted of the interaction between three irrigation regimes (RI: 120% of crop evapotranspiration (ETc) (control); WS1: 100% ETc (moderate water stress); and WS2: 80% ETc (severe water stress)) and three cowpea planting dates (PD1 (two weeks before maize); PD2 (simultaneous with maize) and PD3 (two weeks after maize)) in a maize-based intercropping system, in addition to sole maize and sole cowpea. Each plot measured 21 m² (3 × 7 m) and consisted of 10 ridges spaced 0.70 m apart. Wheat was grown as the preceding crop in both seasons, sown in November and harvested in late April.

2.4. Crops Establishment and Management

Maize (hybrid TWC310) was planted at a density of 57,600 plants/ha (100% recommended density), with 25 cm spacing between hills (one plant per hill). The maize hybrid TWC310 was sown on May 15th and May 21st during the first and second growing seasons, respectively, either as a monoculture or within an intercropping system. The harvest occurred on September 1st and 7th in the first and second growing seasons, respectively. Fertilization of maize included 357 kg/ha calcium superphosphate (15.5% P_2O_5) and 119 kg/ha potassium sulfate (48% K_2O) applied during soil preparation. Nitrogen fertilizer (ammonium nitrate, 33.3% N) was applied to maize at 285.6 kg/ha in five equal splits at 10-day intervals after 21 days from planting.

Cowpea (*Vigna unguiculata* L., cv. Cream) was planted at the recommended density for both sole and intercropped systems (72 kg seeds/ha, 100% recommended density). The sole cowpea was planted on both sides of the ridge, with 15 cm spacing between hills (one plant per hill). The intercropped cowpea was planted on the opposite side of maize ridge, with 15 cm spacing between hills (two plants per hill). Sole cowpea was sown on May 15th and May 20th in the first and second seasons, respectively. Two harvests were conducted for both sole and intercrops cowpea: the first at 60 days after sowing and the second at maize harvest. Nitrogen fertilizer (ammonium nitrate, 33.3% N) was applied to cowpea at 84 kg/ha in one dose 3 weeks after planting.

2.5. Crop-soil water relations

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

$$ETc = ETo\ x\ kc$$

1

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

ETo values were computed utilizing the Penman-Monteith equation (Allen et al., 1998). The kc values for maize, as documented by Taha and Kasem (2022), are 0.35, 0.98, 1.12, and 0.45 for the initial, developmental, middle, and end seasons, respectively, and were employed to ascertain the requisite irrigation water depth in accordance with Allen et al. (1998).

The measurements of water consumptive use (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 & Hansen, (1962) as follows:

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

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 & Jopling, 1984):

$$\mathrm{AIW} = \frac{\mathrm{ETo} \times \mathrm{I}}{\mathrm{Ea}\,(1 - \mathrm{LR})}$$

3

where AIW = applied irrigation water depth (mm day^{-1}) and Ea = application efficiency equal to 85% for the drip irrigation system. I= interval, Ea= application efficiency, LR = leaching requirements (was not considered). We presumed that the irrigation water supplied to

the intercropped maize suffices to meet the water requirements of its intercropping systems with soybean, as reported by Taha and Abdel-Wahab et al., (2024) and Taha and Kasem (2022).

Irrigation was conducted at predetermined intervals of every two days using the drip lateral lines. Four lines on the top of the raised beds for intercropping system and sole cowpea and two lines for sole maize. These lines are connected to the sub-main line. Each lateral line is 20 m long and spaced at 0.70 m on the sub-main and is equipped with build-in emitters of 2 L/h discharge rate spaced at 0.30 m on the lateral lines. A differential pressure tank was connected to the drip irrigation system to inject fertilizer via irrigation water.

The maize grain yield, both from intercropping and monoculture, was determined by harvesting and weighing all plants within the experimental plot area, followed by aggregating the weights of all plots. The output from both cuts of cowpea was combined to determine the total forage yield. The biomass from all examined intercropping systems was gathered from the field post-harvest. The experiment was conducted at the same site utilized in the initial growing season throughout the subsequent growing season.

2.6. Soil Analysis

Soil samples were collected before planting and after harvest from three depths (0–20, 20–40, and 40–60 cm). Soil organic matter was determined using the Walkley–Black method and calculated by multiplying organic carbon by 1.724 (Walkley and Black, 1934). Nitrogen was quantified using the micro-Kjeldahl method (Hesse, 1971). While, the quantification of available phosphorus in soil was conducted using stannous chloride (SnCl2) using UV-Vis spectrophotometry (Jackson 1973).

2.7. Evaluation of Intercropping Performance

2.7.1. Land Equivalent Ratio (LER)

To evaluate the efficiency of the studied cowpea-maize intercropping systems in land use, LER was utilized. LER is an assessment of the land use efficiency of the intercropping system (Rao and Willey, 1980) and is computed as follows:

$$LER = \mathrm{LERA} + \mathrm{LERB} = \frac{YintA}{YmonoA} + \frac{yintB}{YmonoB}$$

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.

2.7.2. Water equivalent ratio (WER)

WER quantifies the water volume necessary for individual crops to achieve yields comparable to those obtained with one unit of water in intercrops, as determined by the formula proposed by Mao et al. (2012):

$$\mathrm{WER} = [(\mathrm{Yint,A/WUint})/(\mathrm{Ymono,A/WUmono,A})] + [(\mathrm{Yint,B/WUint})/(\mathrm{Ymono,B/WUmono,B})]$$

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.

2.7.3. Change in water use (ΔWU)

The index of ΔWU by the intercrops developed by 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 difference 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 respective proportions in the intercrop (WUint, exp). The anticipated water consumption in intercropping correlates with the water utilization of each species in monoculture and the relative yield achieved in intercropping compared to monoculture (partial LER). Consequently, this formula employs the partial land equivalent ratio of crops A and B as coefficients for ΔWU (Mao et al., 2012), as delineated below:

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

6

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

7

Both WER and ΔWU evaluate whether a particular intercrop yield (consisting of two species) would be achieved with augmented water (WER > 1; ΔWU < 0) or diminished water (WER < 1; ΔWU > 0) relative to that employed in monocultures.

2.7. Evaluation of economic performance

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

Total income (US $ ha^{-1}) = (yield A × price A) + (yield B × price B) (8)

where A and B denote sole and intercropped species, respectively. The prices utilized in the analysis were obtained from the farm prices as follows: The prices per tonne for cowpea and maize in the first season were 184.76 and 32.13 USD/ton, respectively, while in the second season, the prices were 315.44 and 27.42 USD/ton, respectively.

Additionally, the monetary advantage index (MAI) was derived from the LER values. The analysis elucidates the economic benefits of the intercropping system, with a positive MAI value signifying its advantages. The MAI was computed following the approach defined by Ghosh (2004).

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

2.7 Statistical analysis

Statistical analysis was performed independently for maize and cowpea yields in both sole and intercropped scenarios, adhering to the methodologies outlined by Gomez and Gomez (1984). Mean comparisons were conducted utilizing the least significant difference (LSD) test at the 5% significance level, as delineated by Waller and Duncan (1969).

3. Results

3.1. Characterization of the meteorological conditions at the experimental location

Figure 4 illustrates the mean temperature, solar radiation, and wind speed during the first growing season (4a) and the second growing season (4b). The figure indicated substantial fluctuations in these meteorological factors across the two growing seasons, with more pronounced variations observed in the second season. This suggested that it could influence the value of evapotranspiration (ETo), the primary determinant of water requirements.

Figure 5 illustrates a comparison of the computed monthly ETo values during the first and second growing seasons. The figure indicated elevated ETo values during the second growing season in comparison to the first growing season in June, July, and August. Consequently, it is anticipated that the values of applied irrigation water treatments will be elevated in the second growing season compared to the first, along with water consumption.

3.1.1. The utilized irrigation water

Table 3 delineates the anticipated volumes of irrigation water utilized in the examined treatments for both sole maize and its intercropping systems with cowpea, in addition to sole cowpea. The irrigation quantities assigned to sole maize were identical to those allotted for the intercropping system with PD2 and PD3. The designated irrigation volume for the intercropping system with PD1 included the irrigation water amount applied to cowpea two weeks prior to maize cultivation, together with the water allotted to maize. Table (3) indicates that the irrigation water utilized for both sole and intercropped crops was higher in the second growing season compared to the first, due to increased seasonal ETo values (Fig. 5).

Water stress treatments of 100% and 80% ETc led to a 19% and 40% reduction in irrigation water applied to maize and its intercropping systems during the first growing season, respectively, in comparison to the requisite irrigation quantities. During the second growing season, the reductions were 17% and 34%, respectively, in relation to the necessary irrigation quantities. Irrigation water applied to sole maize and sole cowpea diminished by 19% and 39%, respectively, while employing 100% and 80% ETc during the first growing season, in comparison to the required irrigation levels. During the second growing season, the amounts of water applied were reduced by 16% and 36% with the application of 100% and 80% ETc, respectively, compared to the required irrigation volumes (Table 3).

Table 3
Utilized irrigation water (mm) for sole maize, sole cowpea, and their intercropping systems throughout various cowpea planting dates.

	First growing season			Second growing season		
	RI	WS_1	WS_2	RI	WS_1	WS_2
Sole maize	1193	961	710	1271	1026	771
Sole cowpea	665	501	362	708	563	381
Intercropped maize in PD1	1264	1020	757	1340	1081	811
Intercropped maize in PD2	1193	961	710	1271	1026	771
Intercropped maize in PD3	1193	961	710	1271	1026	771

RI, WS_1, and WS_2= irrigation with 120, 100, and 80% ETc, respectively, PD1 = cowpea planted two weeks before maize cultivation, PD2 = cowpea planted in the same date as maize cultivation, PD3 cowpea planted two weeks after maize cultivation.

3.1.2. Water consumptive use

Table 4 indicated that the water consumption values for maize intercropping systems exceeded those of sole maize owing to the inclusion of intercropped cowpea. This result demonstrated that water loss by evapotranspiration and/or deep percolation decreased with the increase of ground cover from intercropped cowpea. The peak water consumption occurred when cowpea was sown two weeks prior to maize, due to the substantial irrigation applied, which created enhanced ground cover before maize planting, thereby it could minimize evaporation losses. Moreover, increased water consumption was seen in the second growing season compared to the first, due to rising monthly ETo values (Fig. 5).

The results presented in Table 4 indicate improved utilization of the applied water, resulting in reduced water losses due to deep percolation within this intercropping system. The extensive ground cover provided by cowpea is also credited with reducing soil evaporation. Furthermore, the contrasting rooting patterns of cowpea and maize (deep versus shallow roots) enhanced access to soil moisture at various depths and allowed for the more extensive utilization of soil volume, hence optimizing water usage efficiency.

Table 4
Water consumptive use (mm) of sole maize, sole cowpea and their intercropping systems varying cowpea planting dates.

	First season			Second season		
	RI	WS_1	WS_2	RI	WS_1	WS_2
Sole maize	916	799	625	1131	893	663
Sole cowpea	599	446	319	630	490	328
Intercropped maize in PD1	1038	890	649	1093	938	689
Intercropped maize in PD2	998	875	639	1011	913	671
Intercropped maize in PD3	998	865	639	1011	913	671

RI, WS_1, and WS_2= irrigation with 120, 100, and 80% ETc, respectively, PD1 = cowpea planted two weeks before maize cultivation, PD2 = cowpea planted in the same date as maize cultivation, PD3 cowpea planted two weeks after maize cultivation.

3.2. The yields of sole and intercropped maize across different irrigation regimes

Significant differences (*p < 0.05)* were noted between the yield of sole maize and its yield in the three intercropping systems, as well as across the three irrigation regimens in the first growing seasons. Whereas, in the second growing season, there were significant differences ($p < 0.05$) between the yield of sole maize and its yield in the three intercropping systems, as well as across the three irrigation regimens and the interaction between them (Table 5).

Table 5 indicates that intercropped maize production increased in the second growing season relative to the first, irrespective of irrigation volume or cowpea planting date. This enhancement is ascribed to the residual effects of cowpea as a leguminous crop on soil health, resulting from biological nitrogen fixation by the legume in the second season compared to the first season.

Moreover, the findings in Table 5 indicated a decline in sole maize yield during the second season compared to the first, attributed to the depleting effect of maize as a cereal crop on soil nutrients. The yield of intercropped maize was inferior to that of sole cultivation when cowpea was sown two weeks prior to maize in both growing seasons and across all irrigation treatments. This may be due to interspecific competition for light and soil nutrients between cowpea and maize, with cowpea rapidly establishing ground cover earlier by two weeks before maize cultivation. The yield of intercropped maize was higher than that of sole maize cultivation when cowpea was sown on the same day as maize planting and when cowpea was intercropped two weeks subsequent to maize cultivation. This outcome is ascribed to minimal interspecific competition for light and soil nutrients between cowpea and maize, enabling maize plants to utilize available resources well.

The yield of sole maize decreased under conditions of water scarcity, with irrigation with 100% and 80% ETc resulting in losses of 14% and 40% in yield, respectively, during the first growing season. During the second growing season, the decrease was 15% and 42% under irrigation with 100% and 80% ETc, respectively. A more significant reduction in the yield of intercropped maize was observed when cowpea was sown simultaneously with maize or two weeks later, both subjected to water stress treatments, due to interspecific competition for water between the cowpea and maize plants. Nevertheless, intercropping cowpea in the same date as maize cultivation and two weeks after diminishes maize yield losses due to reduced interspecific competition for water. These results were consistent over both growing seasons (Table 5).

Table 5
The maize yields (ton/ha) in sole and intercropped systems with varying cowpea planting dates (CS) and irrigation treatments (IR) during both growing seasons

Cropping system	**First growing season**				**Second growing season**			
	RI	**WS_1**	**WS_2**	**Mean**	**RI**	**WS_1**	**WS_2**	**Mean**
Sole maize	6.90	5.93	4.15	5.66	6.64	5.63	3.85	5.37
Intercropped maize in PD1	5.56	4.75	3.29	4.53	5.68	4.81	3.22	4.57
Intercropped maize in PD2	7.21	6.06	4.18	5.82	7.42	6.19	4.12	5.91
Intercropped maize in PD3	7.34	6.23	4.25	5.94	7.76	6.52	4.35	6.21
Mean	6.75	5.74	3.97		6.88	5.79	3.89	
$LSD_{0.05}$								
IR	1.36				0.63			
CS	1.03				1.34			
IR X CS	NS				2.33			

RI, WS_1, and WS_2= irrigation with 120, 100, and 80% ETc, respectively, PD1 = cowpea planted two weeks before maize cultivation, PD2 = cowpea planted in the same date as maize cultivation, PD3 = cowpea planted two weeks after maize cultivation, NS= nonsignificant.

3.3. The productivity of sole and intercropped cowpea under various irrigation regimes

Table 6 indicates significant differences *(p < 0.05)* in cowpea yields between sole and intercropped systems across the three irrigation treatments, as well as the interaction effects of irrigation treatments and cropping systems in both growing seasons.

Table 6 illustrates that, with the required irrigation, the yield of sole cowpea was higher than that of intercropped cowpea in both growing seasons due to the interspecific competition between cowpea and maize plants under intercropping, with an enhancement in the second season relative to the first, ascribed to cowpea residual effect in the soil. The yield of intercropped cowpea was maximized when planted two weeks prior to maize cultivation and minimized when planted two weeks subsequent to maize cultivation in both growing seasons.

Under the applied water stress treatments, the yield of sole cowpea decreased by 9% and 32% for those irrigated at 100% and 80% ETc, respectively, averaged over the two growing seasons, compared to yields achieved under optimal irrigation conditions (Table 6). Elevated yield reductions were noted for intercropped cowpea under both water stress conditions, likely due to interspecific competition for water between cowpea and maize.

Table 6
The sole and intercropped cowpea yields (ton/ha) under its intercropping systems with maize (CS) and irrigation treatments (IR) over both growing seasons.

Cropping system	First growing season				Second growing season			
	RI	WS_1	WS_2	Mean	RI	WS_1	WS_2	Mean
Sole cowpea	58.08	53.04	41.04	50.72	59.48	54.34	42.24	52.02
Cowpea in PD1	48.24	43.44	33.36	41.68	49.54	44.64	34.46	42.88
Cowpea in PD2	36.24	31.68	24.24	30.72	37.44	32.78	25.24	31.82
Cowpea in PD3	33.12	28.80	21.84	27.92	34.22	29.80	22.74	28.92
Mean	43.92	39.24	30.12	37.76	45.17	40.39	31.17	38.91
$LSD_{0.05}$								
IR	0.65				1.96			
CS	0.73				1.06			
IR X CS	1.27				1.83			

RI, WS_1, and WS_2= irrigation with 120, 100, and 80% ETc, respectively, PD1 = cowpea planted two weeks before maize cultivation, PD2 = cowpea planted in the same date as maize cultivation, PD3 = cowpea planted two weeks after maize cultivation.

3.4. Soil fertility assessment

3.4.1. Soil organic matter

Table 7 displays the quantified values of soil organic matter following the harvest of sole maize and its intercropping systems throughout the three examined irrigation treatments. The quantified concentration of soil organic matter before cultivation was 0.31%. The table indicated that the quantified levels of soil organic matter were the lowest during exclusive maize farming.

The table's results indicated that the percentage increase in soil organic matter correlates with the duration of the cowpea growing season, with the most significant increase occurring when cowpea was planted two weeks prior to maize cultivation, and the least increase observed when cowpea was planted two weeks subsequent to maize cultivation. This tendency was noted with the application of necessary irrigation quantities. Whereas, under water stress treatments, a similar trend was seen with a reduction in the values of soil organic matter (Table 7).

Table (7): Soil organic matter (SOM%) following the harvest of sole maize and its intercropping systems with cowpea, along with the percentage variation in soil organic matter under the examined irrigation regimens.

	SOM after harvest			Percentage of difference in SOM		
	RI	WS_1	WS_2	RI	WS_1	WS_2
Sole maize	0.29	0.27	0.23	-6	-13	-26
Intercropped maize in PD1	0.38	0.36	0.34	23	16	10
Intercropped maize in PD2	0.37	0.35	0.33	19	13	6
Intercropped maize in PD3	0.36	0.34	0.32	16	10	3

RI, WS_1, and WS_2= irrigation with 120, 100, and 80% ETc, respectively, PD1 = cowpea planted two weeks before maize cultivation, PD2 = cowpea planted in the same date as maize cultivation, PD3 = cowpea planted two weeks after maize cultivation.

3.4.2. Available soil nitrogen

Table 8 presents the impact of sole maize, its intercropping systems, and irrigation interventions on soil accessible nitrogen. The findings indicated significant differences *($p < 0.05$)* in nitrogen levels between sole and intercropped systems across the three irrigation treatments, as well as the interaction effects of irrigation treatments and cropping systems in both growing seasons.

Table 8 indicated that the concentrations of accessible nitrogen in the soil were higher in all maize intercropping systems compared to sole maize irrigated with the three irrigation regimes. The highest concentrations of soil nitrogen were seen when cowpea was sown two weeks prior to maize. Table 8 reveals that increased levels of soil accessible nitrogen were noted in the second growing season, in contrast to those documented in the first growing season, due to the residual effect of cowpea as a leguminous crop.

Furthermore, available soil nitrogen levels declined under both water stress regimes; however, under these conditions, maize intercropping systems maintained higher levels of available soil nitrogen than sole maize cultivation during both growing seasons (Table 8), hence underscoring the benefits of intercropping leguminous crops such as cowpea with maize.

Table 8
Soil nitrogen availability (mg/kg) influenced by sole maize, its intercropping systems (CS), and irrigation treatments (IR) over both growing seasons.

Cropping systems	First growing season				Second growing season			
	RI	WS_1	WS_2	Mean	RI	WS_1	WS_2	Mean
Sole maize	11.39	10.00	8.96	10.12	11.99	10.12	9.02	10.38
Intercropped maize in PD1	14.39	12.79	10.87	12.68	14.49	13.04	11.33	12.95
Intercropped maize in PD2	13.30	11.82	10.23	11.78	13.80	12.04	10.73	12.19
Intercropped maize in PD3	12.20	10.28	9.35	10.61	12.40	10.54	9.74	10.89
Mean	12.82	11.22	9.85		13.17	11.44	10.21	
$LSD_{0.05}$								
IR	0.27				0.27			
CS	0.42				0.39			
IR X CS	0.74				0.68			

RI, WS_1, and WS_2= irrigation with 120, 100, and 80% ETc, respectively, PD1 = cowpea planted two weeks before maize cultivation, PD2 = cowpea planted in the same date as maize cultivation, PD3 = cowpea planted two weeks after maize cultivation.

3.4.3. Available soil phosphorus

Table 9 illustrates the effect of sole maize, its intercropping systems, and irrigation practices on soil available phosphorus. The results in Table 9 indicated significant differences *($p < 0.05$)* in soil accessible phosphorus among the intercropping systems and irrigation treatments across both seasons, as well as their interaction.

Similar results to the available soil nitrogen were noted for available soil phosphorus, which exhibited increased levels across all maize intercropping systems compared to sole maize irrigated under the three irrigation regimes. The highest concentrations of soil available phosphorus were seen when cowpea was grown two weeks prior to maize (Table 9).

Furthermore, increased levels of soil accessible phosphorus were noted in the second growing season, unlike those documented in the first growing season, due to the residual effect of cowpea, which may lead to increased yields in the following season. Furthermore, the quantities of soil accessible phosphorus decreased under both water stress treatments (Table 9).

Nevertheless, intercropping, in conjunction with both water stress treatments, led to increased soil accessible phosphorus levels compared to those recorded under sole maize in both growing seasons (Table 9), hence augmenting the benefits of intercropping leguminous crops like cowpea with maize.

Table 9
Available soil phosphorus (mg/kg) influenced by sole maize, its intercropping systems (CS), and irrigation treatments (IR) over both growing seasons.

Cropping systems	**First growing season**				**Second growing season**			
	RI	**WS_1**	**WS_2**	**Mean**	**RI**	**WS_1**	**WS_2**	**Mean**
Sole maize	4.11	3.89	3.65	3.88	3.21	2.98	2.75	2.98
Intercropped maize in PD1	5.88	5.19	4.17	5.08	6.38	5.69	4.57	5.55
Intercropped maize in PD2	5.52	4.73	3.91	4.72	6.01	5.22	4.32	5.18
Intercropped maize in PD3	5.17	4.29	3.81	4.42	5.68	4.78	4.21	4.89
Mean	5.17	4.53	3.89		5.32	4.67	3.96	
$LSD_{0.05}$								
IR	0.07				0.37			
CS	0.09				0.34			
IR X CS	0.16				0.58			

RI, WS_1, and WS_2= irrigation with 120, 100, and 80% ETc, respectively, PD1 = cowpea planted two weeks before maize cultivation, PD2 = cowpea planted in the same date as maize cultivation, PD3 = cowpea planted two weeks after maize cultivation.

3.5. Evaluation of Intercropping Performance

3.5.1. Land Equivalent Ratio (LER)

Table 10 displays the values of partial LER for cowpea (LER_{cowpea}), partial LER for maize (LER_{maize}), and total LER (LER_{total}) across both growth seasons. The table results demonstrated that the values of LER_{cowpea} were maximized when cowpea was planted two weeks prior to maize, and diminished when cowpea was sown concurrently with maize or two weeks subsequent to maize planting. Conversely, the highest values of LER_{maize} were attained when cowpea was sown two weeks after maize, and these values diminished when cowpea was planted concurrently with maize or two weeks before maize planting. The results remain consistent throughout the three irrigation regimes in both growing seasons.

The highest values of LER_{total} were recorded when cowpea was sown concurrently with maize, observed across all three irrigation regimes in both growing seasons.

Moreover, the findings indicated elevated values of LER_{cowpea}, LER_{maize}, and LER_{total} in the second growing season, attributable to increased yields of both crops during this period, in contrast to the first growing season, when irrigated adequately. Moreover, these values were elevated in the second growing season in comparison to the first growth season (Table 10).

The implementation of the two water stress treatments led to a decrease in the values of LER_{cowpea}, LER_{maize}, and LER_{total} due to diminished yields of both intercrops across both growing seasons. Nonetheless, the implementation of the two water stress treatments during the second growing season yielded greater LER_{total} values compared to those recorded under the three irrigation treatments in the

first growing season. These findings demonstrate the contribution of cowpea to enhancing land and resource-use efficiency, boosting soil fertility through its nitrogen-fixing capability, and the potential for increased total yields relative to monocropping (Table 10).

Table 10
The land equivalent ratios (LER) influenced by maize intercropping systems (IS) under the examined irrigation treatments (IR) across both growing seasons.

Irrigation treatment	Intercropping systems	First growing season			Second growing season		
		LER_{cowpea}	LER_{maize}	LER_{total}	LER_{cowpea}	LER_{maize}	LER_{total}
RI	PD1	0.83	0.81	1.64	0.83	0.86	1.69
	PD2	0.62	1.04	1.67	0.63	1.12	1.75
	PD3	0.57	1.06	1.63	0.58	1.17	1.74
WS1	PD1	0.81	0.80	1.61	0.82	0.85	1.68
	PD2	0.60	1.02	1.62	0.60	1.11	1.71
	PD3	0.54	1.05	1.59	0.54	1.16	1.70
WS2	PD1	0.81	0.79	1.61	0.82	0.84	1.65
	PD2	0.59	1.03	1.62	0.60	1.07	1.67
	PD3	0.53	1.02	1.56	0.54	1.12	1.66

RI, $WS_{1,}$ and WS_2= irrigation with 120, 100, and 80% ETc, respectively, PD1 = cowpea planted two weeks before maize cultivation, PD2 = cowpea planted in the same date as maize cultivation, PD3 = cowpea planted two weeks after maize cultivation.

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

The results for WER_{cowpea}, WER_{maize}, and WER_{total} are displayed in Table 11. The peak WER_{cowpea} values across the three irrigation treatments were recorded when cowpea was sown prior to maize in both growing seasons. The peak values of WER_{maize} and WER_{total} were recorded when cowpea was cultivated following maize during both growth seasons. Moreover, the values of partial and total WER were heightened during the second growing season relative to those in the first growing season. The increased WER_{total} in the second growing season, attributed to the residual effects of cowpea on the soil, improved soil water retention, hence positively affecting the yield of intercropped maize (Table 11).

Moreover, the application of water stress treatments resulted in diminished partial and total WER values during both growing seasons. Nevertheless, the WER_{total} values under WS1 during the second growing season exceeded those under RI in the first growing season (Table 11). Consequently, intercropping with legumes can improve water usage efficiency for maize, particularly under conditions of moderate water stress.

Table 11 demonstrates that the three intercropping systems attained total WER values above 1 and ΔWU values below 0, even under water stress conditions, signifying improved water use efficiency.

Table 11
The water equivalent ratios (WER) and change in water use (ΔWU) influenced by maize intercropping systems (IS) under the studied irrigation treatments (IR) in both growing seasons.

IR	IS	First growing season				Second growing season			
		WER_{cowpea}	WER_{maize}	WER_{total}	ΔWU	WER_{cowpea}	WER_{maize}	WER_{total}	ΔWU
RI	PD1	0.48	0.71	1.19	-0.17	0.48	0.89	1.37	-0.26
	PD2	0.37	0.96	1.33	-0.17	0.39	1.25	1.64	-0.29
	PD3	0.34	0.98	1.32	-0.14	0.36	1.31	1.67	-0.27
WS1	PD1	0.41	0.70	1.11	-0.11	0.43	0.81	1.24	-0.19
	PD2	0.30	0.91	1.21	-0.05	0.32	1.05	1.37	-0.15
	PD3	0.28	0.95	1.23	-0.03	0.29	1.10	1.40	-0.14
WS2	PD1	0.40	0.79	1.19	-0.15	0.39	0.80	1.19	-0.15
	PD2	0.29	1.01	1.30	-0.07	0.29	1.03	1.32	-0.10
	PD3	0.27	1.02	1.29	-0.03	0.26	1.09	1.35	-0.08

RI, $WS_{1,}$ and WS_2= irrigation with 120, 100, and 80% ETc, respectively, PD1 = cowpea planted two weeks before maize cultivation, PD2 = cowpea planted in the same date as maize cultivation, PD3 = cowpea planted two weeks after maize cultivation.

3.6. Evaluation of economic performance

Table 12 exhibited increased total income figures for all assessed intercropping systems relative to maize monoculture, with the highest values attained when cowpea was intercropped two weeks prior to maize cultivation across the three irrigation regimes in the first growing season. Conversely, in the growing second season, the maximum total income values were achieved when cowpea was intercropped two weeks after maize cultivation across all three irrigation regimes. This result attributed to higher maize price in the second season compared to the first season, which suggests that the combined yield and income from the intercropping systems exceed those from sole maize cultivation.

Furthermore, positive values of MAI were attained in both growing seasons. The values of MAI followed the same trend as total income, where it was the highest when cowpea was intercropped two weeks prior to maize cultivation across the three irrigation regimes in the first growing season. In the second growing season, the maximum total income values were achieved when cowpea was intercropped two weeks after maize cultivation across all three irrigation regimes (Table 12).

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

	RI		WS_1		WS_2	
	TI (USD/ha)	**MAI**	**TI (USD/ha)**	**MAI**	**TI (USD/ha)**	**MAI**
	First growing season					
Sole maize	1,275	--	1,096	--	767	--
Intercropped maize in PD1	2,577	1,006	2,273	861	1,680	636
Intercropped maize in PD2	2,497	1,002	2,138	818	1,551	594
Intercropped maize in PD3	2,420	935	2,077	771	1,487	534
Second growing season						
Sole maize	2,095	--	1,776	--	1,214	--
Intercropped maize in PD1	3,150	1,286	2,741	1,110	1,961	772
Intercropped maize in PD2	3,367	1,443	2,851	1,184	1,992	799
Intercropped maize in PD3	3,386	1,440	2,874	1,183	1,996	793

RI, $WS_{1,}$ and WS_2= irrigation with 120, 100, and 80% ETc, respectively, PD1 = cowpea planted two weeks before maize cultivation, PD2 = cowpea planted in the same date as maize cultivation, PD3 = cowpea planted two weeks after maize cultivation.

4. Discussion

4.1. Meteorological Conditions Effects on Irrigation Water Requirements and Water Consumption

The observed differences in applied irrigation water and water consumptive use between the two growing seasons can be primarily attributed to variations in meteorological conditions, particularly evapotranspiration demand. The higher values of ETo recorded during the second growing season, especially in the summer months (Fig. 5), reflects increased atmospheric demand driven by higher temperature, solar radiation, and wind speed (Fig. 4). These climatic factors are well established as the main drivers of crop water requirements, explaining the increased irrigation volumes and water consumption observed across all treatments. The increase in applied irrigation water under higher ETo conditions highlights the sensitivity of irrigation scheduling to climatic variability.

Furthermore, the cultivation of PD1 resulted in higher total applied irrigation water to the system, compared to PD2 and PD3 due to early planting of cowpea (Table 3). Under arid environments such as Middle Egypt, small changes in temperature and radiation can significantly alter crop water requirements, reinforcing the need for adaptive irrigation management. Similar findings were reported by Taha and Kasem (2022), who demonstrated that irrigation water requirements for maize-based systems closely follow seasonal evapotranspiration patterns.

Water consumptive use followed a similar trend, with higher values recorded in the second growing season (Table 4). This reflects not only increased atmospheric demand but also enhanced crop transpiration under warmer conditions. However, the results indicate that intercropping systems exhibited more efficient water use despite higher total consumption. The presence of cowpea increased ground cover, which reduced direct soil evaporation and improved the partitioning of water toward productive transpiration. This agrees with Zhang et al. (2022), who reported that improved canopy cover reduces evaporative losses and enhances water-use efficiency.

Furthermore, intercropping influenced soil–water dynamics through complementary resource use. The contrasting rooting systems of maize and cowpea allowed for water extraction from different soil depths, thereby improving the utilization of available soil moisture and reducing unproductive water losses (Gebru, 2015). This complementarity is particularly important under water-limited conditions, where efficient use of soil moisture determines system performance. The role of intercropping in modifying the crop microclimate also contributed to improved water-use patterns. Reduced daytime evaporation and improved nighttime moisture retention have been associated with intercropped systems (He et al., 2011), while enhanced soil moisture conservation and reduced evaporation have been

documented in maize–cowpea systems (Ghanbari et al., 2010). Additionally, the rapid canopy development and extensive leaf area of cowpea can improve soil shading and reduce moisture loss, thereby mitigating the negative effects of water stress (Layek et al., 2018).

Overall, these findings demonstrate that while climatic variability increases crop water requirements, intercropping systems can partially offset these effects by improving water-use efficiency and soil moisture conservation. This highlights the importance of integrating crop diversification strategies with climate-responsive irrigation management to enhance the sustainability of agricultural systems under arid conditions.

4.2. Influence of Intercropping and Water Stress on Crop Productivity

The results demonstrate that both intercropping configuration and water availability play a decisive role in determining the productivity of maize- and cowpea-based systems under arid conditions. The observed increase in intercropped maize yield in the second growing season highlights the cumulative benefits of legume integration, particularly through residual soil fertility improvements associated with biological nitrogen fixation (Table 5). This finding is consistent with Ouda et al. (2020), who reported that legumes enhance soil nutrient status over time, thereby supporting subsequent crop performance. The transfer of biologically fixed nitrogen from cowpea to maize during the growing season further contributes to improved productivity in intercropping systems (Shen and Chu, 2004). In contrast, the decline in sole maize yield in the second season reflects the limitations of continuous monocropping systems, where nutrient depletion and soil degradation can reduce productivity over time (Fujisao et al., 2020). These results underscore the importance of crop diversification as a strategy for maintaining long-term productivity and sustainability in maize-based systems.

The effect of cowpea planting date on maize yield reveals a clear trade-off between competition and complementarity. Early cowpea planting reduced maize yield due to increased interspecific competition for light and nutrients, as cowpea established canopy cover earlier than maize (Megawer et al., 2010). In contrast, simultaneous or delayed planting minimized competition and allowed maize to better exploit available resources, resulting in higher yields. Similar trends have been reported in previous studies (Ouda et al., 2020; Mishra, 2019; Zohry et al., 2017), confirming that appropriate temporal arrangement is critical for optimizing intercropping performance.

Water stress significantly reduced the yield of both maize and cowpea (Tables 5 and 6), highlighting the sensitivity of these crops to limited water availability. The reduction in maize yield under 100% and 80% ETc reflects the direct impact of water deficit on physiological processes such as photosynthesis and biomass accumulation (Song et al., 2019). However, the magnitude of yield reduction varied depending on the intercropping system. Under water stress conditions, increased competition for water between maize and cowpea became more pronounced, particularly when both crops were established simultaneously or when cowpea was planted after maize. This resulted in greater yield reductions in intercropped maize under these configurations.

For cowpea, the decline in yield under intercropping compared to sole cropping is primarily attributed to its lower competitive ability, especially under shading from maize (Eskandari, 2012). The effect was most pronounced when cowpea was planted after maize, due to stronger competition for light and soil resources, as also reported by Abou-Keriasha et al. (2011). Furthermore, water stress exacerbated yield reductions in cowpea, despite its moderate drought tolerance (Vasconcelos et al., 2020), indicating that interspecific competition can override physiological tolerance under limited water availability.

The interaction between intercropping and water stress also highlights the dual nature of resource complementarity. While differences in root architecture between maize (fibrous roots) and cowpea (taproot system) can enhance water uptake from different soil layers under adequate conditions (Mugi-Ngenga et al., 2023), this complementarity may shift toward competition under water deficit conditions (Senghor et al., 2023). This transition explains the greater yield penalties observed under severe water stress.

From a sustainability perspective, these findings emphasize that productivity in intercropping systems is highly dependent on management practices, particularly planting date and water availability. Properly managed intercropping systems can enhance productivity through improved resource use and nutrient cycling, while poorly timed configurations may increase competition and reduce yields. Therefore, optimizing intercropping design is essential to achieving sustainable intensification, especially under water-limited conditions.

4.3. Influence of Intercropping and Water Stress on Soil Fertility

The results clearly demonstrate that cowpea–maize intercropping significantly enhances soil fertility compared to sole maize cultivation, particularly through improvements in soil organic matter, nitrogen, and phosphorus availability (Tables 7, 8 and 9). The decline in soil organic matter under sole maize reflects the well-documented limitations of continuous cereal monocropping, where reduced organic inputs and rapid residue decomposition contribute to soil degradation (Balík et al., 2020). In contrast, the incorporation of cowpea into

the system increased soil organic matter, highlighting the role of legumes in improving soil carbon inputs and supporting long-term soil health.

The magnitude of improvement in soil organic matter was closely linked to cowpea planting date, with earlier planting resulting in greater increases. This can be attributed to longer growth duration and higher biomass production, which enhance organic residue return to the soil. However, the reduction in soil organic matter under water stress conditions suggests that limited water availability restricts biomass production and residue inputs, thereby constraining soil carbon accumulation (Table 7). Similar findings were reported by Drăghici et al. (2024), who showed that water stress can negatively affect organic matter dynamics through reduced plant growth.

Intercropping also significantly improved soil nitrogen availability, primarily due to biological nitrogen fixation by cowpea. The higher nitrogen levels observed in intercropped systems, particularly when cowpea was planted earlier, reflect the combined effects of increased nitrogen fixation and improved nutrient cycling (Table 8). Previous studies have shown that legumes can fix substantial amounts of atmospheric nitrogen and contribute to soil fertility (Vasconcelos et al., 2020), while also enhancing nitrogen availability for associated cereal crops (Nasar et al., 2021). In addition, intercropping has been reported to stimulate nodulation processes and nitrogen fixation through root interactions and rhizosphere effects (Hu et al., 2021).

A similar trend was observed for soil phosphorus availability, which was consistently higher in intercropping systems compared to sole maize (Table 9). This improvement is largely attributed to the ability of cowpea roots to release organic acids that enhance phosphorus solubilization and availability (Dahmardeh et al., 2010). Changes in rhizosphere chemistry, including increased acidification and microbial activity, further contribute to improved phosphorus dynamics in intercropping systems (Latati et al., 2014). Additionally, cowpea's adaptive mechanisms for phosphorus acquisition under low-availability conditions, such as the exudation of organic acids, can enhance nutrient accessibility in the soil (Gustiningsih, 2023; Wang et al., 2015).

The increase in soil organic matter, soil nitrogen, and soil phosphorus in the second growing season further indicates a residual effect of cowpea, which contributes to sustained improvements in soil fertility over time. Similar residual benefits of legume intercropping have been reported by Ghosh et al. (2007), Gaspar et al., (2018) and Ouda et al. (2020), emphasizing the importance of legumes in maintaining soil productivity in cropping systems.

However, water stress reduced soil nitrogen, likely due to its negative effects on nodule formation and nitrogen fixation processes (Melo et al., 2025), demonstrating the sensitivity of biological nitrogen fixation to soil moisture conditions. As with nitrogen, water stress reduced phosphorus availability, likely due to limited nutrient mobility and reduced plant uptake under low soil moisture conditions (Moursi et al., 2013). Despite this reduction, intercropping systems maintained higher soil organic matter, nitrogen and phosphorus levels than monocropping, indicating their greater resilience under water-limited conditions.

From a sustainability perspective, these findings highlight the critical role of legume-based intercropping in enhancing soil fertility and supporting long-term agricultural productivity. By improving soil organic matter, increasing nutrient availability, and promoting efficient nutrient cycling, legumes intercropping systems contribute to the restoration and maintenance of soil health. Moreover, the persistence of these benefits under water stress conditions underscores their importance as a strategy for sustainable intensification in arid environments.

4.4. Resource-Use Efficiency and Economic Performance of Intercropping Systems

The results clearly demonstrate that cowpea–maize intercropping enhances both land and water-use efficiency, as well as economic returns, compared to monocropping systems. The consistently high land equivalent ratio (LER > 1) across all treatments confirms the superiority of intercropping in utilizing available land resources. The variation in partial LER values between maize and cowpea reflects differences in competitive ability and resource capture, which are strongly influenced by cowpea planting date. Early cowpea planting favored cowpea dominance, while delayed planting enhanced maize performance. However, the highest total LER values were obtained when both crops were planted simultaneously, indicating an optimal balance between competition and complementarity (Table 10). Similar findings were reported by Abou-Keriasha et al. (2011), who highlighted the importance of temporal arrangement in maximizing intercropping efficiency.

The increase in LER values during the second growing season further reflects the cumulative benefits of intercropping, particularly through improved soil fertility and enhanced crop performance. Comparable LER values reported in previous studies in Egypt (El-Ghobashy et al., 2018; Elsaid et al., 2019; El-Ghobashy et al., 2020; El-Shamy et al., 2022; Salama et al., 2022; Shehata and Hamd-Alla,

2023) confirm the robustness of cowpea–maize intercropping systems under different management conditions. Although water stress reduced LER values, they remained above unity, indicating that intercropping maintained its advantage over monocropping even under limited water availability.

Water-use efficiency, as indicated by WER and ΔWU, showed similar trends. The WER values greater than 1 and negative ΔWU values across all intercropping systems demonstrate that higher productivity was achieved per unit of water compared to monocropping systems, even under water stress conditions (Table 11). These findings align with Mao et al. (2012), who reported significant improvements in water-use efficiency in intercropping systems. The higher WER values observed in the second growing season can be attributed to improved soil conditions and enhanced water retention associated with the residual effects of cowpea.

The variation in WER components further reflects the interaction between crop growth dynamics and resource use. Early cowpea planting enhanced WER for cowpea, while delayed planting improved WER for maize, indicating differential resource capture over time. The overall improvement in WER_{total} when cowpea was planted after maize suggests that reduced interspecific competition for water enhances system efficiency (Table 11). Similar observations were reported by Taha and Kasem (2022), who demonstrated improved water-use efficiency in maize–cowpea systems. Moreover, intercropping systems have been shown to improve soil moisture conservation and water extraction efficiency through complementary root systems (Dube et al., 2014; Ayele, 2020), as well as increased root density and reduced evaporation losses (Pankou et al., 2021).

The persistence of WER values above unity under water stress conditions highlights the potential of intercropping as a strategy for improving water productivity in arid environments. Moderate water stress (WS1) maintained relatively high WER values, supporting the findings of Liu et al. (2025), who reported that intercropping systems can enhance water-use efficiency under limited irrigation. This indicates that intercropping can buffer the negative effects of water scarcity by improving the efficiency of water utilization rather than increasing water input.

From an economic perspective, the higher total income and positive MAI values observed in intercropping systems confirm their economic viability (Table 12). The positive relationship between LER and MAI indicates that improved biological efficiency directly translates into economic benefits, as previously reported by Dhima et al. (2007). The higher economic returns of intercropping systems can be attributed to increased total productivity and more efficient use of inputs (Banik et al., 2006). Similar economic advantages have been reported in other legume-based intercropping systems (Ouda and Zohry, 2025), reinforcing the role of intercropping as a profitable and sustainable agricultural practice.

Overall, these findings highlight that cowpea–maize intercropping enhances resource-use efficiency and economic performance, even under water stress conditions. By improving land productivity, increasing water-use efficiency, and generating higher economic returns, intercropping systems contribute to the key objectives of sustainable intensification in arid agroecosystems.

4.5. Graphical comparison of land, water, and economic performance of cowpea-maize intercropping systems under different irrigation regimes

Figure 6 illustrate a graphical summary compares the performance of the different cowpea-maize intercropping systems across irrigation regimes using three key indices: LER, WER, and MAI. Bars represent the values of each index for the different intercropping–irrigation combinations, allowing direct visual comparison among treatments. LER and WER describe the biological and water-use efficiency advantages of intercropping relative to sole maize cropping, while MAI reflects the associated economic benefit. Presenting these indicators together allows an integrated assessment of productivity, resource-use efficiency, and profitability. Differences among maize intercropping systems and irrigation treatments highlight how system performance responds to water availability, facilitating direct visual comparison of trade-offs and synergies among the evaluated systems.

RI-PD1 = required irrigation applied to cowpea planted two weeks before maize cultivation, RI-PD2 = required irrigation applied to cowpea planted in the same date as maize cultivation, RI-PD3 = required irrigation applied to cowpea planted two weeks after maize cultivation cowpea, WS1-PD1 = irrigation with 100% ETc applied to cowpea planted two weeks before maize cultivation, WS1-PD2 = irrigation with 100% ETc applied to cowpea planted in the same date as maize cultivation, WS1-PD3 = irrigation with 100% ETc applied to cowpea planted two weeks after maize cultivation, WS2-PD1 = irrigation with 80% ETc applied to cowpea planted two weeks before maize cultivation, WS2-PD2 = irrigation with 80% ETc applied to cowpea planted in the same date as maize cultivation, WS2-PD3 = irrigation with 80% ETc applied to cowpea planted two weeks after maize cultivation.

Conclusion

This study demonstrates that cowpea–maize intercropping is an effective strategy for achieving sustainable intensification of maize-based systems under water stress conditions in arid Egypt. Intercropping improved crop productivity, enhanced soil fertility through increased organic matter and nutrient availability, and significantly increased land and water-use efficiency compared to monocropping. Despite reductions in yield under water stress, intercropping systems maintained higher performance and efficiency, indicating greater resilience to water scarcity.

The results also highlight the importance of management practices, particularly planting date and irrigation level, in optimizing the balance between competition and complementarity in intercropping systems. Simultaneous or delayed planting of cowpea relative to maize provided the best combination of productivity and resource-use efficiency.

Overall, integrating cowpea into maize-based systems offers a practical, low-input approach to improving productivity, enhancing soil health, and increasing economic returns under limited water availability. Therefore, cowpea–maize intercropping can be recommended as a climate-smart and sustainable agricultural practice for arid and semi-arid regions.

Declarations

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Figures

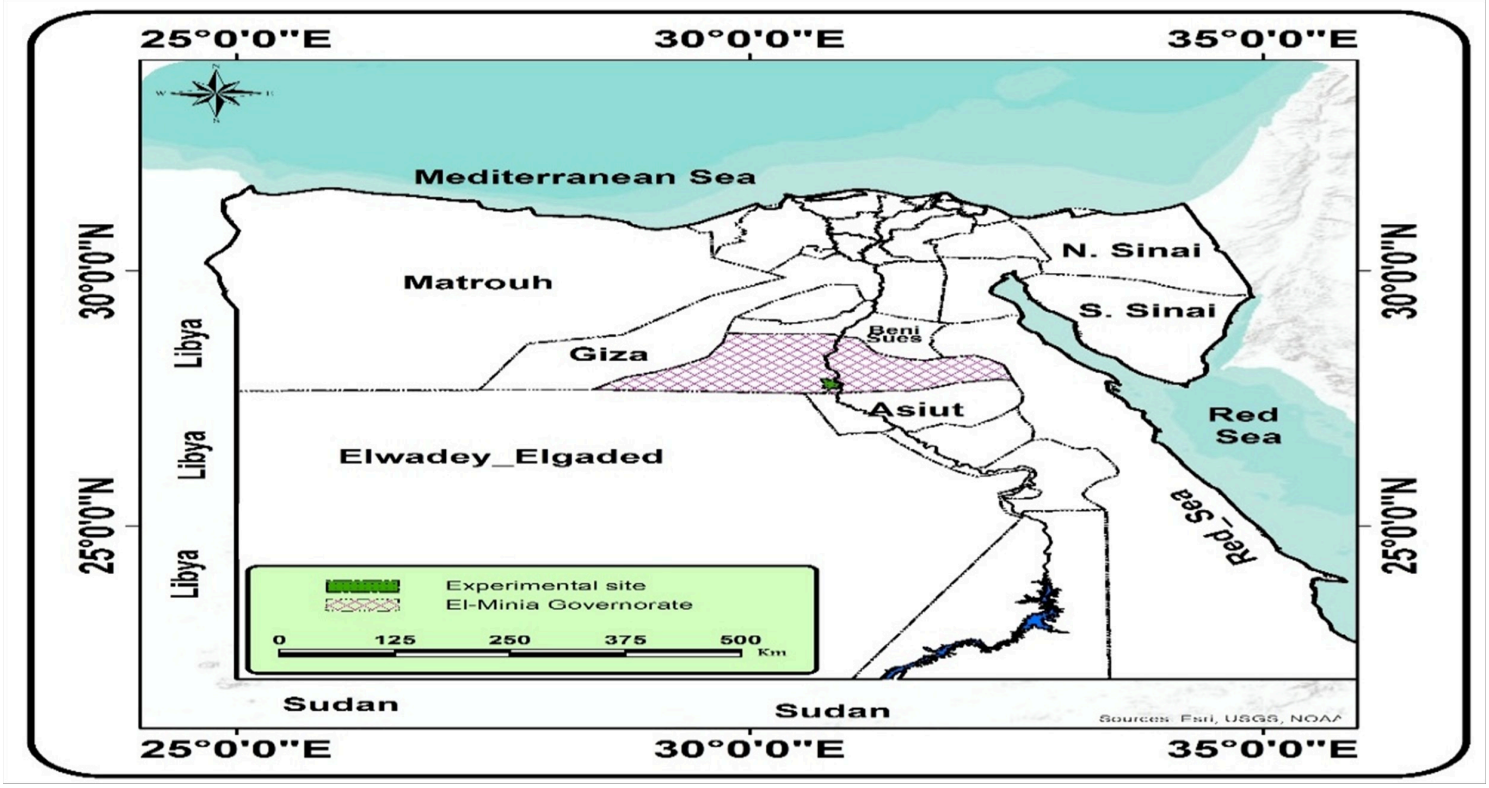


Figure 1

The location of the experimental site at El-Mina Governorate, Egypt.

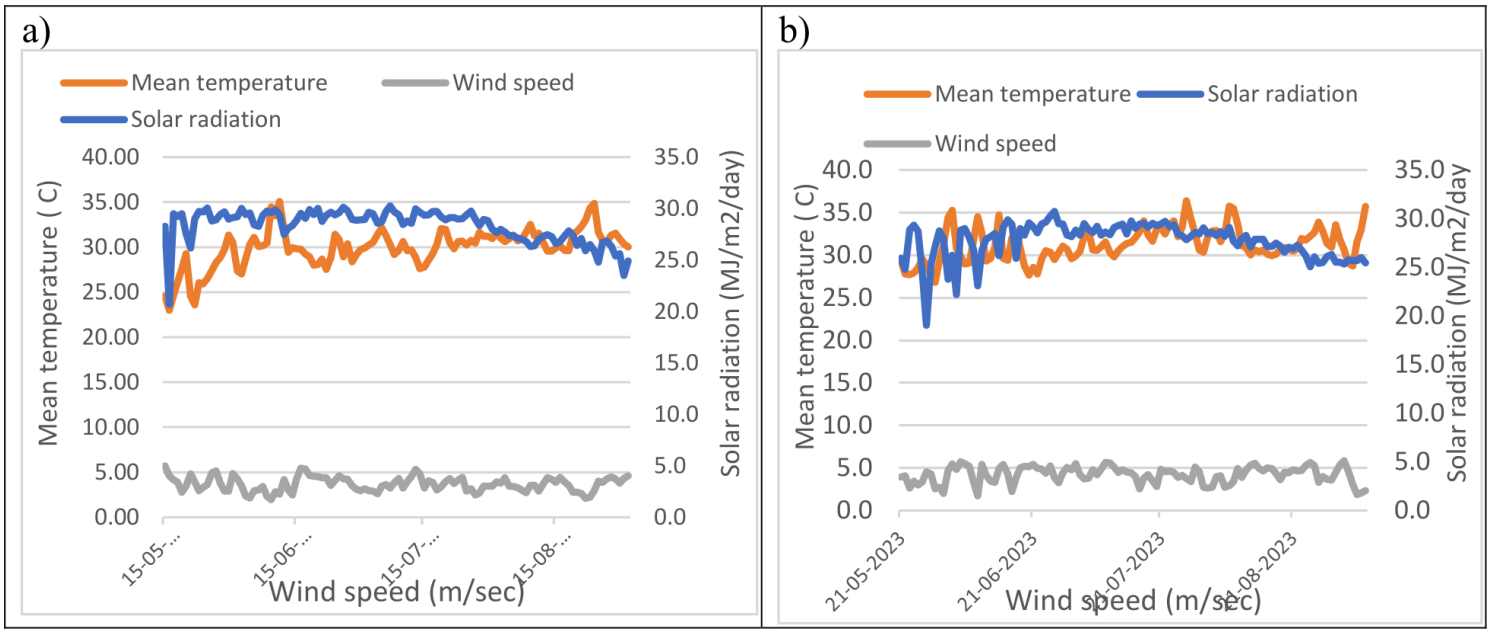


Figure 2

Figure 4: Average temperature, solar radiation, and wind speed during the first growing season (a) and the second growing season (b).

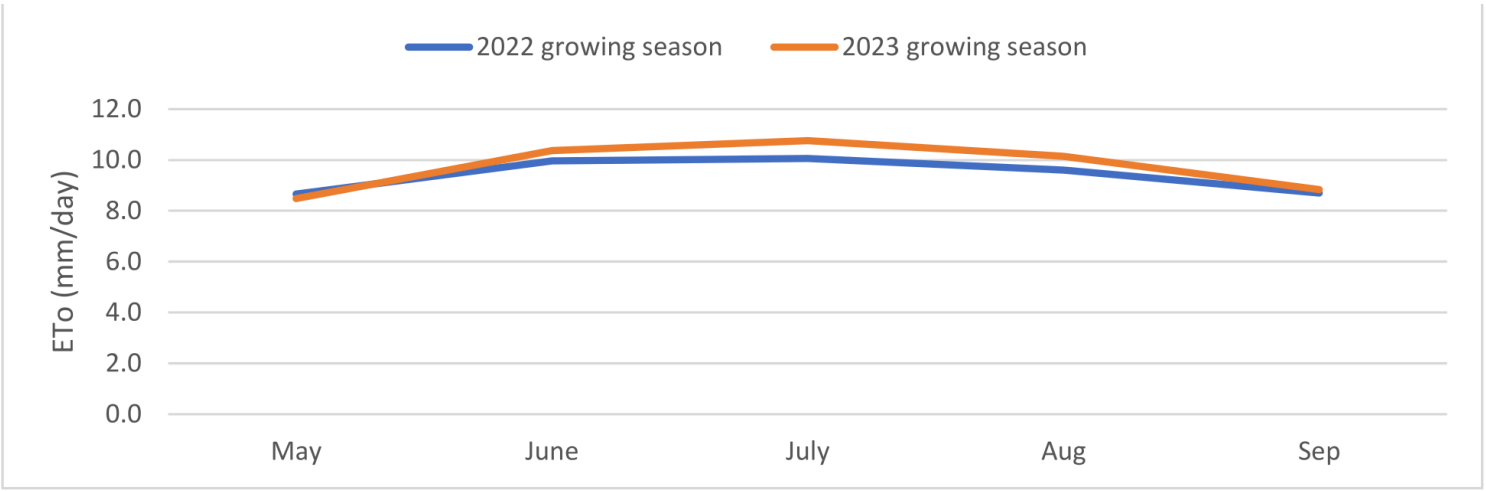


Figure 3

Figure 5: Monthly ETo values in both growing seasons.

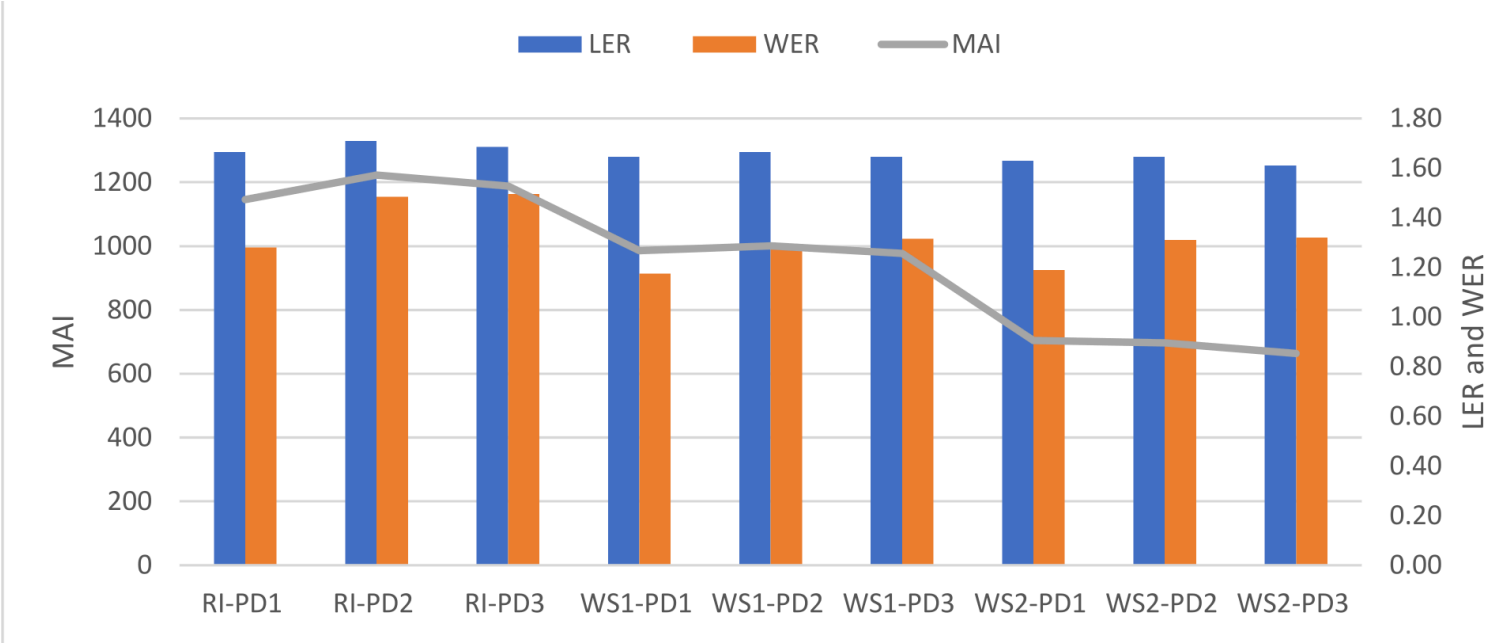


Figure 4

Figure 6: Graphical summary of the performance of the evaluated intercropping systems across irrigation regimes averaged over the two growing seasons.