

Optimizing resource utilization through intercropping soybeans (*Glycine max* (L.) Merr.) and maize (*Zea mays* L.) in Middle Egypt

Samiha OUDA^{1, 2} and Abd El-Hafeez ZOHRY³

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Abstract: The agronomic and economic performance of soybean–maize intercropping under different irrigation regimes and soybean planting densities was assessed during two field seasons (2022–2023) in Egypt. Three irrigation levels were applied: 120 % ETc (optimal), 100 % ETc, and 80 % ETc. Maize was grown at the recommended density in both sole and intercropped systems, while soybean was intercropped at 50 %, 65 %, and 75 % of its recommended density. Increasing soybean density enhanced soybean yield but reduced maize grain yield due to interspecific competition, particularly under drought stress conditions. The highest land equivalent ratio (1.61) was achieved with 75 % soybean combined with full maize density. All intercropping treatments recorded water equivalent ratios greater than unity, with maximum water-use efficiency (1.41) observed at 50 % soybean density. Intercropping significantly increased soil nitrogen and available phosphorus compared with sole maize, with greater improvements at higher soybean densities. Economic analysis revealed that 75 % soybean–100 % maize combination produced the highest economic returns across irrigation regimes. Despite yield reductions under water stress, intercropping consistently outperformed monocropping in productivity and profitability. These results confirm that soybean–maize intercropping is a sustainable approach to enhance land and water use efficiency, soil fertility, and farm income under water-limited conditions.

Key words: land and water equivalent ratios, monetary advantage index, planting density, soil nitrogen and phosphorus availability.

Optimiziranje izrabe virov pri skupnem gojenju soje (*Glycine max* (L.) Merr.) in koruze (*Zea mays* L.) v Srednjem Egiptu

Izvleček: Agronomska in gospodarska učinkovitost skupnega posevka soje in koruze pri različnih namakalnih režimih in gostotah setve soje je bila ocenjena v dveh poljskih sezonah (2022–2023) v Srednjem Egiptu. Uporabili so tri stopnje namakanja: 120 % ETc (optimalno), 100 % ETc in 80 % ETc. Koruza je bila gojena pri priporočeni gostoti tako v čistem kot v skupnem posevku, medtem ko je bila soja posejana v 50 %, 65 % in 75 % priporočene gostote. Povečanje gostote soje je povečalo pridelek soje, vendar zmanjšalo pridelek koruznega zrnja zaradi medvrstne konkurence, zlasti v razmerah sušnega stresa. Največje razmerje produktivnosti zemljišč (1,61) je bilo doseženo pri 75 % soje v kombinaciji s polno gostoto koruze. Pri vseh obdelavah mešanega posevka so bila zabeležena razmerja vodnih ekvivalentov večja od enote, z največjo učinkovitostjo porabe vode (1,41), opaženo pri 50 % gostote soje. Mešani posevki so znatno povečali količino dušika in razpoložljivega fosforja v tleh v primerjavi s čistim posevkom koruze, z večjimi izboljšavami pri večjih gostotah posevka soje. Ekonomska analiza je pokazala, da je kombinacija 75 % soje in 100 % koruze ustvarila največje ekonomske donose v vseh namakalnih režimih. Kljub zmanjšanju donosa zaradi pomanjkanja vode je skupno gojenje dosledno prekašalo monokulturo v produktivnosti in donosnosti. Ti rezultati potrjujejo, da je mešano gojenje soje in koruze trajnosten pristop za izboljšanje učinkovitosti rabe zemlje in vode, rodovitnosti tal in dohodka kmetije v razmerah omejene količine vode.

Ključne besede: razmerje ekvivalenta produktivnosti zemlje in vode, indeks denarne prednosti, gostota sajenja, razpoložljivost dušika in fosforja v tleh.

¹ Water Requirements and Field Irrigation Research Department; Soils, Water and Environment Research Institute; Agricultural Research Center; Egypt.

² Corresponding author: samihaouda@yahoo.com

³ Crop Intensification Research Department; Field Crops Research Institute; Agricultural Research Center; Egypt, abdelhafeezzohry@yahoo.com.

1 INTRODUCTION

The growing of soybean (*Glycine max* (L.) Merr.) has become a feasible agricultural strategy in Egypt, tackling issues including food insecurity, dependence on imports, and the need for economic diversification (Naser et al., 2024). Egypt produces a modest quantity of soybeans, approximately 85,000 metric tons, fulfilling less than 3 % of the domestic need (WORLD-GRAIN.com 2024). As a result, Egypt depends significantly on imports to satisfy its considerable soybean consumption, mostly for animal feed (WORLD-GRAIN.com 2025). The primary constraint on enhancing soybean yield is the limited availability of land in the Nile Delta and Valley. Furthermore, the rivalry between soybean and other significant summer crops favors maize cultivation. Consequently, the expansion of soybean farming in sandy soils predominantly situated on the eastern and western peripheries of the Nile Delta and Valley can enhance its productivity. An alternative solution to this issue is intercropping soybean with maize (*Zea mays* L.), which can enhance soybean yield by sharing the planted area and irrigation water allocated to maize. Intercropping soybean with maize in Egypt can enhance soil fertility, land productivity, water use efficiency, and may decrease water loss by soil evaporation, particularly in the country's sandy soils (Song et al., 2022; Nasar et al., 2021; Raza et al., 2021).

Intercropping is an agricultural technique that involves cultivating two or more distinct crops in alternating rows on a certain plot of land simultaneously during their growing season (Federer, 2012). These intercrops often differ in their nutritional needs, root systems, canopy architecture, and the synergistic utilization of growth resources (Lithourgidis et al., 2011). Intercropping soybean with maize is a sustainable agricultural strategy that involves cultivating both crops concurrently in the same field, often in a specific pattern, to optimize resource utilization while providing advantages such as increased yield, improved nutrient absorption, and enhanced overall productivity compared with monoculture farming (Nasar et al., 2021; Liu & Zhao, 2023). Studies demonstrate that intercropping can provide greater outputs than monoculture, with certain research highlighting a superior relative yield advantage for maize and soybean intercropping systems (Nasar et al., 2021). Intercropping often outperforms monoculture due to complementary resource use between component crops. In maize–soybean systems, differences in canopy structure, rooting patterns, and nitrogen acquisition—particularly biological nitrogen fixation by soybean—reduce competition and enhance overall productivity. This complementarity is reflected in relative yield total values greater than one, indicating a yield advantage of intercropping over sole cropping (Li et al., 2014; Nasar et al., 2021).

The planting density of soybean in a maize intercrop-

ping system considerably influences its yield and the overall productivity of the system. Increasing soybean density can improve yield per unit area; however, excessively high densities may intensify competition with maize, reducing individual plant yields because of shading and competition for resources (Li et al., 2024). Determining the ideal soybean density is essential for optimizing the advantages of intercropping, such as enhanced land use efficiency and the possibility of greater overall yield (Wang et al., 2023). Typically, augmenting soybean density can enhance total soybean yield in the intercropping system, since a greater number of plants contribute to the overall harvest (Li et al., 2024). Nonetheless, increased soybean densities may exacerbate competition with maize for essential resources such as sunlight, water, and nutrients, particularly beneath the canopy of the taller maize plants (Wang et al., 2023).

Establishing the optimal planting density of soybean intercropped with maize is essential for minimizing competitive interactions, maximizing maize yield, and improving water-use efficiency. An effective intercropping system requires a balance between increasing plant population and limiting interspecific competition to avoid yield penalties (Wang et al., 2023). However, studies conducted in Egypt on optimal soybean planting density in maize–soybean intercropping systems on the old clay soils of the Nile Delta and Valley have produced inconsistent results. Rashwan & Zen El-Dein (2017) evaluated different soybean and maize planting densities under two intercropping arrangements: 50 % soybean with 100 % maize and 66.7 % soybean with 66.7 % maize of their respective recommended rates. Their findings indicated that the highest soybean yield was obtained from the 66.7 % soybean + 66.7 % maize system, whereas the greatest maize yield and the highest land equivalent ratio (LER = 1.31) were achieved under the 50 % soybean + 100 % maize configuration. Similarly, El-Sherif & Ali (2015) investigated the effects of deficit irrigation (100 %, 85 %, and 70 % of reference evapotranspiration, ETo) on a 50 % soybean–50 % maize intercropping system. Optimal crop yields and resource-use efficiency were recorded at 100 % ETo, resulting in an LER of 1.41 and a water-use efficiency of 1.11 kg m⁻³. Metwally et al. (2017) reported that maximum soybean yield was achieved under a 100 % soybean + 100 % maize intercropping system irrigated at 125 % of maize water requirements, while the highest maize yield occurred with 50 % soybean + 100 % maize at the same irrigation level. Notably, the greatest water-use efficiency was observed in the 100 % soybean + 100 % maize system irrigated with 100 % of maize water requirements. More recently, Taha & Abdel-Wahab (2024) assessed the water equivalent ratio (WER) of soybean–maize intercropping under 50 %, 75 %, and 100 % of the recommended soybean rate combined with 100 % of the maize rate. Their results showed that the highest WER (1.33) was achieved with the 75 % soybean

+ 100 % maize intercropping arrangement. Intercropping systems are extensively advocated as a sustainable agricultural practice due to their presumed potential to improve resource-use efficiency, ecological stability, and agro-biodiversity in comparison to monoculture cropping systems. Nonetheless, these advantages are not universally applicable and may entail trade-offs between effective resource acquisition and heightened interspecific competition, especially in conditions of restricted water and nutrient availability. In Egypt, the intercropping of soybean and maize has been thoroughly examined utilizing various planting densities, spatial configurations, and management strategies. Notwithstanding this extensive research, the documented impacts on maize and soybean yield, land equivalent ratio, and overall system performance are markedly inconsistent and occasionally conflicting. These disparities suggest that intercropping results are significantly limited by boundary circumstances, such as irrigation practices, soil fertility levels, and interactions of crop densities. Previous research has predominantly concentrated on yield-based metrics under

relatively favorable conditions, although a comprehensive assessment of water use efficiency in soybean–maize intercropping across different levels of water availability is still lacking. Furthermore, data about the effects of this intercropping system on economic sustainability and the enhancement of soil fertility, especially in low-fertility sandy soils, is limited. In light of the expanding maize production-consumption gap in Egypt and escalating water scarcity, it is imperative to determine soybean planting densities that mitigate maize yield loss while optimizing land productivity, water use efficiency, soil fertility, and economic returns in water-limited conditions.

2 MATERIALS AND METHODS

This study consists of a two-year field experiment carried out throughout the consecutive seasons of 2022 and 2023 in El-Minia Governorate, Middle Egypt (28.2847° N, 30.5279° E), focusing on maize intercrop-

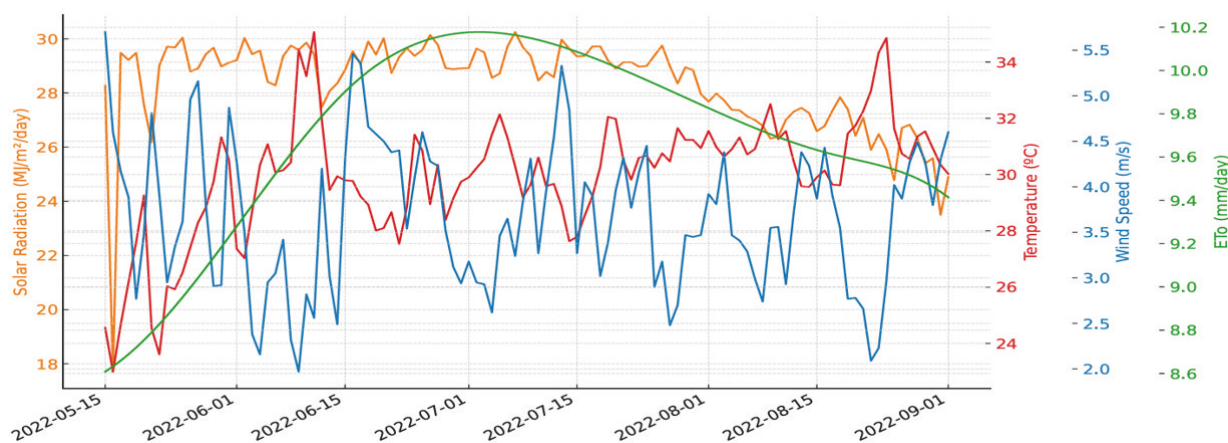


Figure 1: Seasonal weather elements at the experimental site in the first growing season.

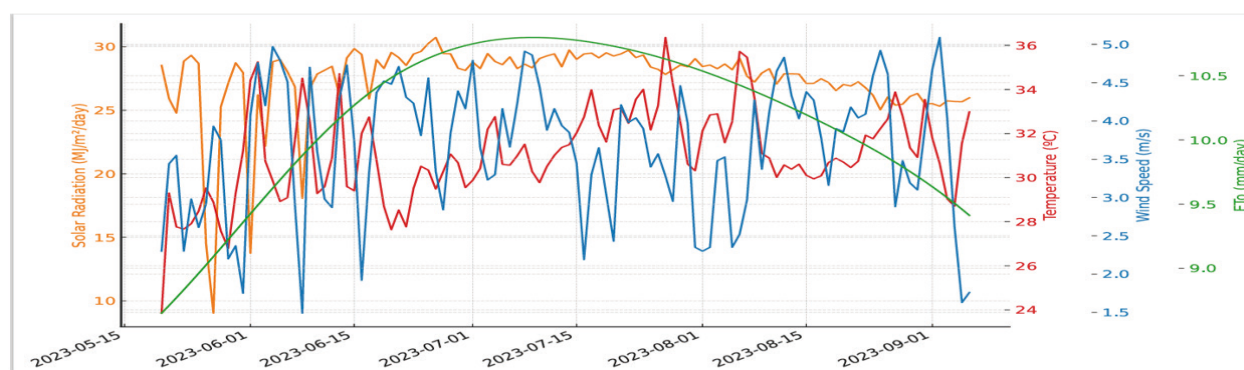


Figure 2: Seasonal weather elements at the experimental site in the second growing season.

ping systems with three plant densities of soybean under three irrigation treatments (additive intercropping systems, where maize planting density was 100 % of its recommended rate, in addition to the intercropped planting densities of soybean). The experimental region exhibits an arid climate characterized by cold winters and scorching, dry summers (Masoued, 2017). Data on average daily air temperature, relative humidity, and wind speed for the studied seasons were acquired from the weather station situated 320 meters from the experimental area (Figure 1 and 2).

The soil at the experimental site is categorized as sandy soil. The soil's physical and chemical variables were assessed following the methodologies of Klute, (1986) and Tan, (1996) (Tables 1 and 2). The irrigation water was sourced from groundwater, with an electrical conductivity of $0.92 \text{ dS}^{-1} \text{ m}$ and a pH of 7.53.

The experimental design employed a split-plot framework with three replicates. The treatments comprised the interaction of three irrigation levels with three soybean planting densities (50 %, 65 %, and 75 % of the recommended rate), intercropped with 100 % of the recommended maize planting density, in addition to sole maize or sole soybean crops. The irrigation treatments included the required irrigation amount (RI), set at 120 % of crop evapotranspiration (ETc) as the control treatment, alongside two water stress treatments: WS1, representing 100 % ETc , and WS2, representing 80 % ETc . The 120 % ETc irrigation level was selected as the required irrigation

rate because of the sandy soil texture and elevated temperatures at the experimental site, which create increased evaporative demand and plant water stress, especially in the examined additive intercropping systems where the total plant density surpasses 100 %. The irrigation treatments were allocated to the main plots, whilst the four cropping systems (three soybean-maize intercropping systems, in addition to sole maize or sole soybean) were designated to the sub-plots within each main plot. Both main plots and subplots were randomized independently within each replicate, giving a total of 36 experimental units ($3 \times 3 \times 4$).

The plot area encompassed 12.6 m^2 ($4.2 \times 3.0 \text{ m}$) and comprised three raised beds, each 1.40 m wide. The preceding crop was wheat in both growing seasons, planted in November and harvested in late April. Figures 3-7 depicts the distinct cultivation of the three soybean intercropping systems with maize, beside sole soybean and sole maize farming.

2.1 MONOCROP AND INTERCROPPED MAIZE

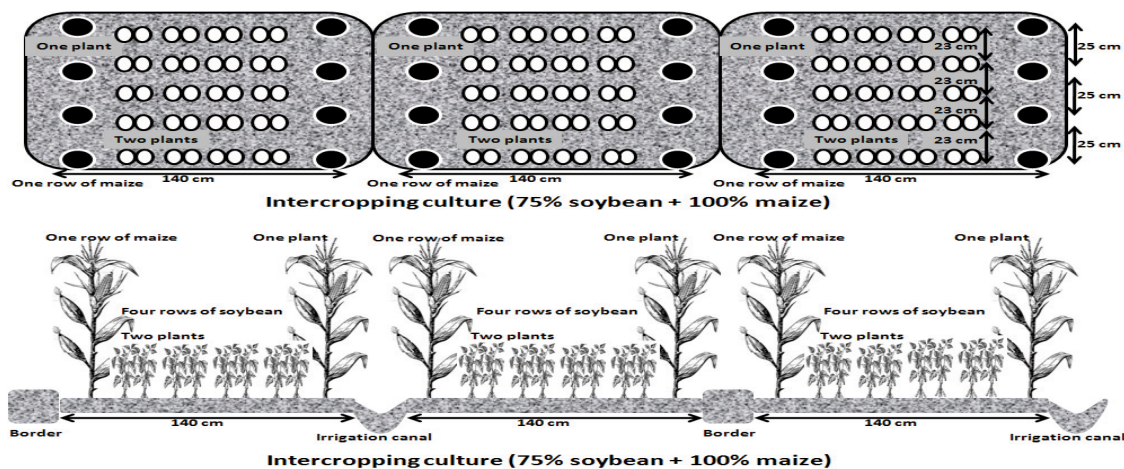
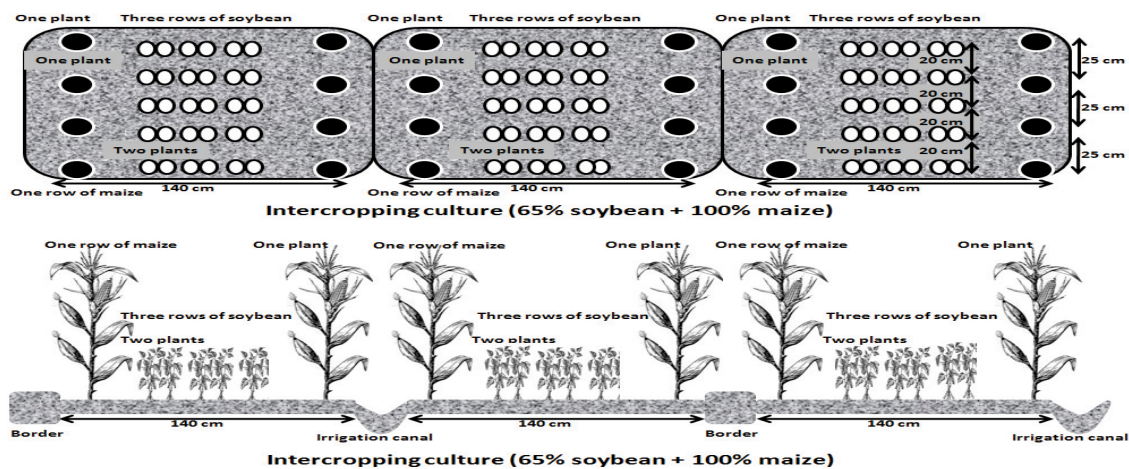
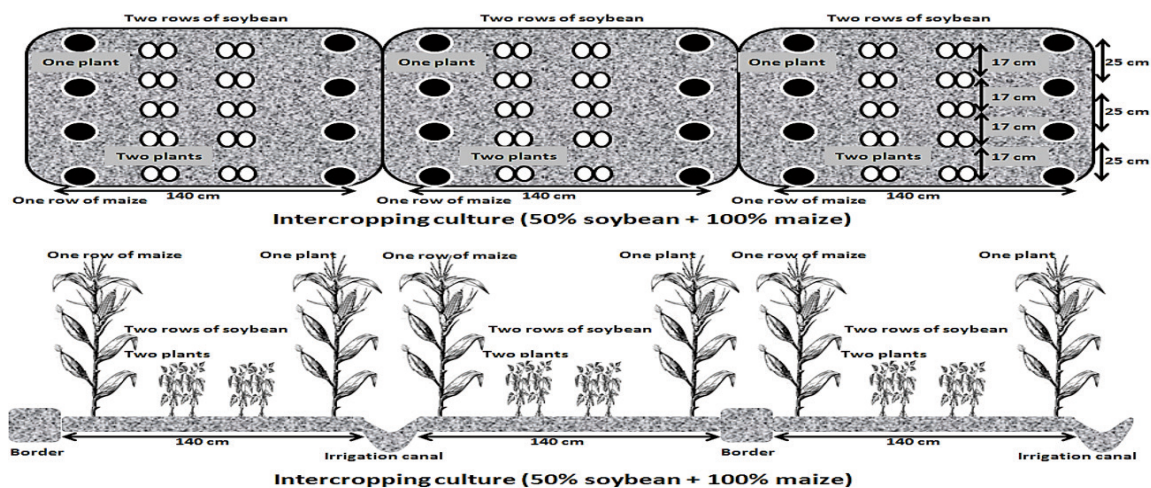
Maize seeds were sown on both sides of the raised beds, maintaining a distance of 25 cm between hills (one plant per stand) and 120 cm between maize rows, in accordance with the complete recommended planting density for both monoculture and intercropped maize (57,600 plants per hectare, 100 % of the recommended rate). The maize hybrid TWC324 was planted on May 15th and 20th in the first and second growing seasons, re-

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

Soil depth (cm)	pH	ECe	Soluble cations (meq l^{-1})				Soluble anions (meq l^{-1})			
	(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^{-1})										
N				P_2O_5			K_2O			
12.14				4.61			58.21			

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



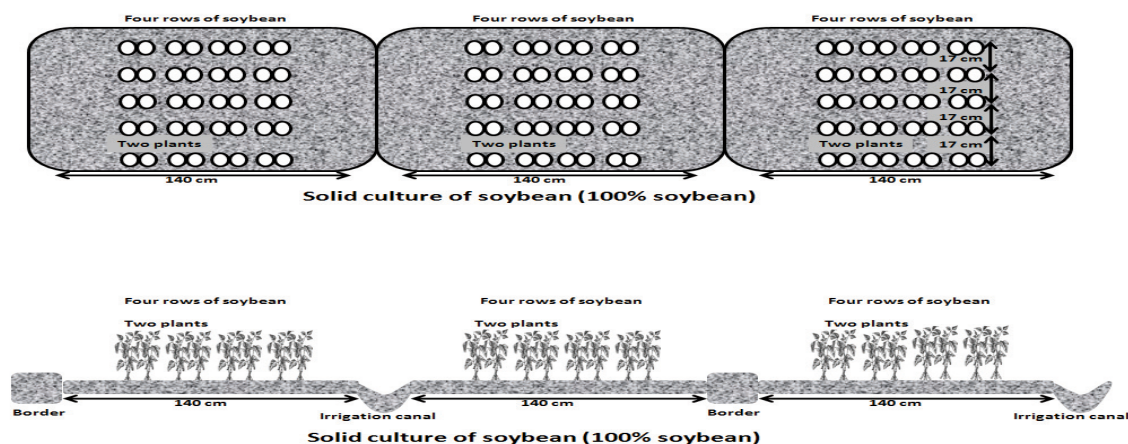


Figure 6: The experimental plots of solid culture of the soybean.

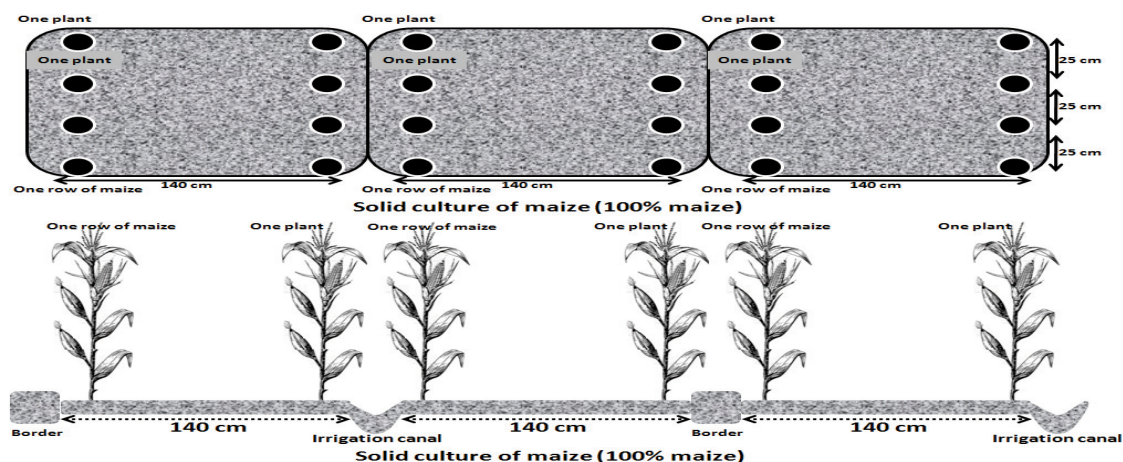


Figure 7: The experimental plots of solid culture of the maize.

spectively, either as a monoculture or in an intercropping system. The harvest occurred on September 1st and 6th during the first and second growing seasons, respectively. Calcium super phosphate (15.5 % P_2O_5) was applied at a rate of 357.0 kg ha⁻¹, and potassium sulphate (48.0 % K_2O) at a rate of 119.0 kg ha⁻¹ was applied during land preparation. Mineral nitrogen fertilizer (ammonium nitrate 33.5 % N) for maize was administered at a rate of 285.6 kg ha⁻¹, divided into five equal applications every 10 days following planting.

2.2 MONOCROP AND INTERCROPPED SOYBEAN

The soybean cultivar Giza111 was utilized in either monoculture or intercropping settings. Both mono and intercropped soybean cultivar inoculated with *Bradyrhizobium japonicum* (Kirchner 1896) Jordan, 1982 before sowing, with Arabic gum utilized as a binding agent. Soybean was sown on May 1st and 5th during

the first and second growing seasons, respectively, and harvested on August 15th and 22nd in the first and second growing seasons, respectively (either as a sole crop or intercropped). The planting densities of intercropped soybean were 50 %, 65 %, and 75 % of the recommended rate (169,412, 216,000, and 250,435 plants ha⁻¹), respectively. These planting densities were selected as a low, medium and highly competitive scenarios as they sought to be more suitable in the low fertile sandy soil of the experimental site. The recommended density for sole soybean is 338,824 plants per hectare. All intercropped soybean densities were sown atop the raised beds. Soybean planting density of 50 % of the recommended density was sown in two rows spaced 20 cm apart in hills 17 cm apart (two plants per hill); 65 % of the recommended density was planted in three rows 20 cm apart in hills 20 cm apart (two plants per hill); and 75 % of the recommended density was planted in four rows 20 cm apart in hills 23 cm apart (two plants per hill). Sole soybean was

planted in four rows, spaced 20 cm apart, in hills 17 cm apart, containing two plants per hill.

2.3 CROP-SOIL WATER RELATIONS

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):

$$ETc = ET_o \times x \times kc \quad (1)$$

where ET_c = crop evapotranspiration (mm day^{-1}), ET_o = reference evapotranspiration (mm day^{-1}), and kc = crop coefficient.

ET_o values were computed utilizing the Penman-Monteith equation (Allen et al., 1998). The kc values for maize, as reported by Taha & Abdel-Wahab et al., (2024), are 0.47, 0.91, 1.01, and 0.44 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 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:

$$WCU = \sum_{i=1}^{i=3} \frac{\theta_2 - \theta_1}{100} \times d \quad (2)$$

where i = number of soil layers, θ_2 = soil moisture content after irrigation, (% by volume), θ_1 = 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):

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

where AIW = applied irrigation water depth (mm day^{-1}) 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 maize suffices to meet the water requirements of its intercropping systems with soybean, as reported by Taha & Abdel-Wahab et al., (2024) and Taha & Kasem (2022). Irrigation was conducted at predeter-

mined intervals of every two days using the drip lateral lines. Four lines on the top of the raised beds for intercropping system and sole soybean 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^{-1} 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 seed production for both intercropping systems and sole crops was ascertained by harvesting and weighing all plants within the experimental plot area, thereafter aggregating the mass of all plots. The biomass of all analyzed cropping systems was collected from the field after harvest. During the second growing season, the experiment was performed at the same location used in the first growing season.

2.4 MEASUREMENT OF SOIL NITROGEN AND PHOSPHORUS

Soil samples were collected before planting and after harvest of sole and intercropped maize to determine available nitrogen and phosphorus. Twelve cores were randomly taken within each treatment using a hand-operated auger, and the process was repeated. Soil samples were air-dried, gently crushed, and then sieved through a 2 mm mesh to get uniform representative samples. Nitrogen was measured with the micro-Kjeldahl method (Hesse, 1971). Available phosphorus in soil was quantified using stannous chloride (SnCl_2) by UV-Vis calorimetry (Jackson, 1973).

2.5 EVALUATION OF THE STUDIED INTERCROPPING SYSTEMS

2.5.1 Land equivalent ratio (LER)

LER is an assessment of the land use efficiency of the intercropping system (Rao & Willey, 1980) and is computed as follows:

$$LER = LER_A + LER_B = \frac{Y_{intA}}{Y_{monoA}} + \frac{Y_{intB}}{Y_{monoB}} \quad (4)$$

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 $LER > 1$, this indicates that a larger area under sole cropping would be required to produce the same yield obtained from the intercropping system, reflecting a land-use advantage of intercropping over monoculture.

2.5.2 Water equivalent ratio (WER)

WER measures the volume of water required for individual crops to attain equivalent yields as those produced with one unit of water in intercrops, calculated using the formula established by Mao et al., (2012):

$$WER = \left[\frac{Y_{int,A}}{Y_{mono,A}} \cdot \frac{WU_{mono,A}}{WU_{int,A}} \right] + \left[\frac{Y_{int,B}}{Y_{mono,B}} \cdot \frac{WU_{mono,B}}{WU_{int,B}} \right] \quad (5)$$

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 and mono crop B, respectively. $WU_{int,A}$, $WU_{mono,A}$, 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.

2.5.3 Change in water use (ΔWU)

The ΔWU index (Morris & Garrity, 1993) was utilized in conjunction with WER to assess the advantages of water use efficiency in intercrops compared to monoculture. ΔWU quantifies the relative discrepancy between the actual water intake in the intercrop ($WU_{int, obs}$) and the expected water use based on the water consumption of the two crop species, modified by weights that represent their respective proportions in the intercrop ($WU_{int, exp}$). The expected water consumption in intercropping is related to the water usage of each species in monoculture and the relative yield attained in intercropping versus monoculture (partial LER). Thus, this formula uses the partial land equivalent ratio of crops A and B as coefficients for ΔWU (Mao et al., 2012) as outlined below:

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

$$\Delta WU = \left[\frac{WU_{int}}{LER_A \times WU_{mono,A}} + (LER_B \times WU_{mono,B}) \right] - 1 \quad (7)$$

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

2.6 ASSESSMENT OF ECONOMIC PERFORMANCE

Total income (TI) and monetary advantage index (MAI) of the intercropping systems were calculated to evaluate the economic advantages of maize intercropping systems relative to sole planting, following the equation reported by Raza et al., (2021):

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

where A and B represent maize and soybean, respectively. The prices employed in the analysis were sourced from the Agricultural Economics Bulletin in Egypt (2021 and 2022) as follows: The prices per tonne for soybean and maize in the first season were 803.02 and 184.76 USD ton⁻¹, respectively, while in the second season, the prices were 708.19 and 315.44 USD ton⁻¹, respectively.

Furthermore, the monetary advantage index (MAI) was calculated based on the LER. It provides clear insights into the economic advantages of the intercropping system. The MAI was calculated according to the methodology established by Ghosh, (2004).

$$MAI = (\text{Value of combined intercrops}) \times (LER - 1) / LER \quad (9)$$

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

2.7 STATISTICAL ANALYSIS

Data from each growing season were analyzed separately using a split-plot analysis of variance (ANOVA) with three replicates. Irrigation treatments were assigned to the main plots, while cropping systems (sole cropping and three intercropping systems) were allocated to the sub-plots. Replicates were treated as blocks. Statistical analyses were performed using MSTAT-C software.

Statistical analysis was performed independently for maize and soybean yields in both sole and intercropped scenarios, adhering to the methodologies outlined by Gomez and Gomez (1984). Treatment 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 AND DISCUSSIONS

3.1 THE IRRIGATION VOLUMES AND THE WATER CONSUMPTION OF BOTH SOLE AND INTERCROPPED CROPS

Table 3 delineates the computed volumes of irrigation water utilized in the examined treatments for both

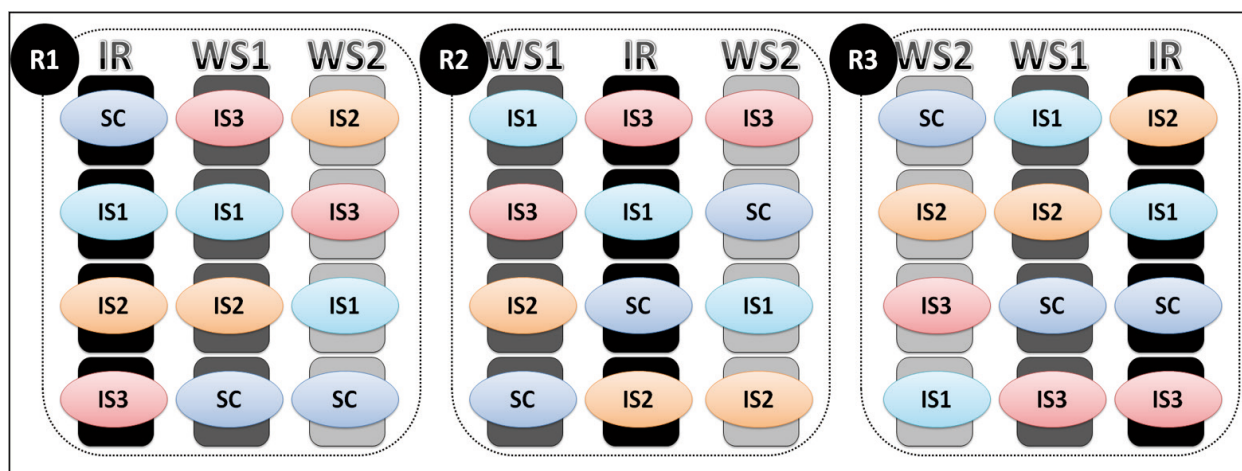


Figure 8: Schematic diagram of the split-plot design used in the experiment. RI, WS1, and WS2 = irrigation with 120, 100, and 80 % ET_c, respectively, IS1, IS2 and IS3 = 50 %, 65 % and 75 % soybean intercropped with 100 % maize, respectively, SC = sole crop (maize or soybean).

sole maize and its intercropping systems with soybean, in addition to sole soybean. Despite the intercropping systems being of the additive type, the irrigation volumes assigned to these systems were identical to those allotted for sole maize cultivation. Taha & Abdel-Wahab et al. (2024) utilized same irrigation quantities for sole maize as those employed in its intercropping systems with soybean. Likewise, Taha & Kasem (2022) intercropped cowpea with maize, utilizing the same irrigation levels for both sole maize and its intercropping system with cowpea.

Table 3 indicates that the implementation of water stress treatments (WS1; 100 % ET_c and WS2; 80 % ET_c) led to a 17 % and 35 % reduction in irrigation water applied to maize and its intercropping systems during the first growing season, respectively, in comparison to the requisite irrigation volumes (RI; 120 % ET_c). During the second growing season, the reductions were 17 % and 34 %, respectively, compared to the RI levels. The irrigation water applied to sole maize and sole soybean fell by 18 % and 33 %, respectively, when utilizing WS1 and WS2 during the first growing season, compared to the RI levels. During the second growing season, the volumes of water applied were reduced by 17 % and 34 % with the use of WS1 and WS2, respectively, compared to RI levels.

The Table also 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 elevated seasonal ETo values (Figure 2 versus Figure 1).

Table 4 indicated that the water consumption estimates for maize intercropping systems exceeded those of sole maize, attributable to the inclusion of intercropped soybean at varying planting densities. This result demonstrated that water loss via evapotranspiration and/or deep

percolation decreased as ground cover from intercropped soybean increased, with the most significant reduction in water loss occurring at 75 % soybean intercropped with 100 % maize, and the least reduction at 50 % soybean intercropped with 100 % maize. Furthermore, increased water consumption was seen in the second growing season compared to the first, related to rising monthly ETo values (Figure 2 versus Figure 1). Reports suggest that while intercropping may lead to increased total water consumption compared to sole cropping, it demonstrates greater water use efficiency, especially when considering the improved yield (Wang et al., 2015).

Our investigation revealed that elevated water consumption correlated with increased soybean planting density, resulting in the enhanced ground cover early in the season, hence lowering water loss via evaporation, as indicated by Zhang et al. (2022). Intercropping soybean

Table 3: Applied irrigation water (mm) to sole maize, sole soybean and their intercropping systems.

	First growing season			Second growing season		
	RI	WS ₁	WS ₂	RI	WS ₁	WS ₂
Sole maize	1393	1161	910	1471	1226	971
Sole soybean	1111	916	741	1195	996	787
50 % soybean + 100 % maize	1393	1161	910	1471	1226	971
65 % soybean + 100 % maize	1393	1161	910	1471	1226	971
75 % soybean + 100 % maize	1393	1161	910	1471	1226	971

RI, WS1, and WS₂ = irrigation with 120, 100, and 80 % ET_c, respectively.

Table 4: Water consumptive use (mm) of sole maize, sole soybean and their intercropping systems

	First growing season			Second growing season		
	RI	WS ₁	WS ₂	RI	WS ₁	WS ₂
Sole maize	1101	917	734	1192	993	794
Sole soybean	914	761	609	1013	844	675
50 % soybean + 100 % maize	1253	1044	835	1360	1134	907
65 % soybean + 100 % maize	1304	1087	869	1417	1180	944
75 % soybean + 100 % maize	1329	1108	886	1445	1204	963

RI, WS₁, and WS₂ = irrigation with 120, 100, and 80 % ETc, respectively.

with maize improves water-use efficiency by promoting complementary use of available resources, with maize often acting as the dominant water absorber (Raza et al., 2022). According to Raza et al. (2021), water uptake in soybean–maize intercropping systems shows both temporal and spatial differentiation: maize tends to consume more water during the early vegetative stage, while soybean water demand increases during its reproductive phase. This finding is supported by Zhang et al. (2022), who reported that temporal complementarity in water use enhances maize kernel development and partially offsets the negative effects of shading during soybean grain filling. Spatial complementarity is observed when intercropped soybean develops greater root length density and allocates proportionally more biomass to roots than shoots, resulting in a more effective spatial distribution of water uptake. In addition, intercropping can modify the microclimate by lowering daytime relative humidity and increasing nighttime relative humidity, thereby reducing plant water loss during the day and helping maintain moisture availability at night (He et al., 2011).

3.2 THE YIELDS OF MAIZE UNDER VARIOUS IRRIGATION REGIMES AND CROPPING SYSTEMS

Maize grain yield was significantly influenced by irrigation regime in both growing seasons ($p \leq 0.05$; Table 5). Across cropping systems, the highest yields were consistently obtained under full irrigation (RI), with mean values of 5.85 and 6.18 t ha⁻¹ in the first and second growing seasons, respectively. Adequate water supply under RI likely supported optimal physiological processes, including photosynthesis, nutrient uptake, and grain filling, resulting in improved maize productivity. In contrast, reducing irrigation levels caused a progressive decline in yield. Moderate water stress (WS₁) reduced maize yield

by approximately 12 % and 10 %, while severe water stress (WS₂) resulted in yield reductions of about 19 % and 17 % in the first and second growing seasons, respectively, relative to RI. These results confirm the strong dependence of maize yield on irrigation water availability, as widely reported for maize grown under arid and semi-arid conditions (Atia et al., 2012; Sah et al., 2020).

Cropping system also exerted a significant main effect on maize yield in both growing seasons ($p \leq 0.05$; Table 5). Sole maize consistently produced the highest grain yield, whereas intercropping with soybean resulted in reduced maize yield during the simultaneous growth period. Averaged across irrigation regimes, maize yield declined progressively as soybean density increased, decreasing from 5.96 t ha⁻¹ in sole cropping to 4.73 t ha⁻¹ when maize was intercropped with 75 % soybean density. This pattern indicates that increasing soybean density intensified interspecific competition for essential resources such as light, nutrients, and soil moisture. Greater canopy overlaps and increased belowground resource demand at higher soybean densities likely shifted the interaction balance toward competition, leading to reduced maize performance (Zhang et al., 2024).

The interaction between irrigation regime and cropping system was not significant for maize yield in either growing season ($p > 0.05$; Table 5). This indicates that the relative ranking and response of cropping systems were consistent across irrigation treatments, and that the effects of irrigation regime and cropping system on maize yield occurred independently. Although numerical differences among treatment combinations were observed, these differences reflect additive main effects rather than a statistically significant interactive response (Mead and Willey, 1980). Thus, water availability did not significantly alter the relative effect of cropping system on maize yield.

Maize yields were generally higher in the second growing season than in the first across all treatments. This improvement may be attributed to more favorable growing conditions and to indirect, system-level benefits associated with soybean inclusion, such as enhanced soil fertility, organic matter content, and improved soil physical properties arising from legume residues. These residual benefits operate temporally and complement maize growth in subsequent seasons, without contradicting the competitive interactions observed during the concurrent growth of maize and soybean (Rücknagel et al., 2016; Wick et al., 2017; Ferreira et al., 2023; Zhou et al., 2024).

Overall, the results demonstrate that while deficit irrigation leads to substantial yield penalties in maize, increasing soybean density in intercropping systems imposes a consistent reduction in maize yield regardless of irrigation regime. Therefore, optimizing irrigation

Table 5: Effect of irrigation treatments , cropping systems and their interaction on maize yields (ton ha⁻¹) in both growing seasons.

Irrigation	cropping system	First growing season	Second growing season	Mean
RI	Sole maize	6.32	6.64	6.48
	50 % soybean + 100 % maize	6.11	6.54	6.33
	65 % soybean + 100 % maize	5.69	5.95	5.82
	75 % soybean + 100 % maize	5.27	5.60	5.44
Mean		5.85	6.18	6.02
WS1	Sole maize	5.72	6.12	5.92
	50 % soybean + 100 % maize	5.46	5.94	5.70
	65 % soybean + 100 % maize	4.96	5.35	5.16
	75 % soybean + 100 % maize	4.47	4.82	4.65
Mean		5.15	5.55	5.35
WS2	Sole maize	5.15	5.82	5.49
	50 % soybean + 100 % maize	5.06	5.56	5.31
	65 % soybean + 100 % maize	4.55	4.9	4.73
	75 % soybean + 100 % maize	3.94	4.29	4.12
Mean		4.67	5.14	4.91
Mean (CS)	Sole maize	5.73	6.19	5.96
	50 % soybean + 100 % maize	5.54	6.01	5.78
	65 % soybean + 100 % maize	5.07	5.40	5.23
	75 % soybean + 100 % maize	4.56	4.90	4.73
LSD _{0.05}				
IR		0.11	0.27	
CS		0.15	0.19	
IR × CS		Ns	ns	

IR = irrigation treatments, CS = cropping systems, RI, WS₁, and WS₂ = irrigation with 120, 100, 80 % ETc, respectively, ns = not significant at $p \leq 0.05$, LSD values are presented only for factors with significant F-test.

management and soybean planting density is essential to balance maize productivity with the broader agronomic and ecological benefits of maize–soybean intercropping systems.

3.3 THE YIELD OF SOLE AND INTERCROPPED SOYBEAN UNDER DIFFERENT IRRIGATION TREATMENTS

Table 6 shows significant differences ($p < 0.05$) in soybean yield between sole cropping and intercropping systems across all three irrigation treatments in both growing seasons. Application of RI resulted in the highest soybean yields, averaging 2.44- and 2.52-ton ha⁻¹ in the first and second seasons, respectively. These results suggest that adequate water availability enhanced soybean growth and productivity by meeting evapotranspiration demands, thereby promoting key physiological

processes such as photosynthesis and nutrient uptake, in agreement with the findings of Morsy et al. (2018).

Irrigation with water stress treatments caused soybean yield reductions of 14 % and 13 % under WS₁, and 24 % and 22 % under WS₂ in the first and second seasons, respectively, compared to yields achieved under RI irrigation. Previous studies have shown that water deficit stress in soybean leads to changes in gas exchange, accompanied by increased leaf temperature and alterations in photosynthetic structures and pigments, including chlorophyll and carotenoids. These changes reduce the plant's ability to convert solar energy into the chemical energy required for essential metabolic processes (Mangena, 2018).

Furthermore, soybean yields either sole or intercropped was significantly affected by cropping systems ($p < 0.05$) in both growing seasons. The results showed that intercropped soybean yield increased as planting density rose from 50 % to 75 % in both growing seasons. This

positive response primarily reflects reduced intraspecific competition and enhanced resource complementarity at lower relative densities, rather than increased competitive pressure from maize. At reduced planting densities, soybean plants experience greater per-plant availability of light, water, and nutrients, allowing more efficient resource capture and compensatory growth, which results in yield percentages exceeding the expected proportional yield of sole soybean cropping (Wang et al., 2023). This indicates that resource complementarity between maize and soybean can offset competitive effects on soybean under optimized density arrangements. In addition, soybean yields—both sole and intercropped—were higher in the second growing season than in the first. This improvement is attributable to temporal complementarity mediated by soybean's residual effects on soil properties, including biological nitrogen fixation and improvements in soil structure through deep rooting, which enhance aeration, drainage, and nutrient cycling (Ennin & Clegg, 2001). These soil-mediated benefits operate independently of direct plant–plant competition and contribute to greater system productivity over time (Ahmad et al., 2025) (Table 6).

Table 6 further indicates that the yield percentage of intercropped soybean exceeded the expected proportional yield relative to sole cropping at corresponding densities. This outcome suggests minimal intraspecific competition among soybean plants at reduced planting densities, which allows more efficient utilization of available growing space and mitigates competition for light, water, and nutrients (Klimek-Kopyra et al., 2021). Consistent with these findings, Kubota et al. (2015) reported that soybean intercropped at 50 % density with maize achieved 52 % of its monoculture yield, exceeding the proportional expectation and reflecting effective niche utilization rather than yield suppression. Intercropping may also improve the canopy light environment, enhancing light penetration and distribution within the crop canopy. Increased light intensity, particularly in the lower canopy layers, can benefit soybean photosynthesis and contribute to improved yield performance under intercropping conditions (Yang et al., 2024). These effects exemplify aboveground resource complementarity, where architectural differences between maize and soybean reduce direct competition for light.

Furthermore, the interaction between irrigation treatments and cropping systems had no significant effect on soybean yield in either growing season ($p > 0.05$). Under water stress conditions, soybean yield declined in both sole and intercropped systems, reflecting resource limitation rather than competitive exclusion. In the first growing season, sole soybean yield decreased by 6 % and 12 % under irrigation at 100 % and 80 % ETc, respec-

tively, relative to required irrigation, while in the second growing season, reductions of 5 % and 15 % were observed (Table 6). Water stress during critical reproductive stages, such as pod set and seed filling, is known to substantially reduce soybean yield, particularly in intercropping systems where competition for water may occur (Abou-Elela et al., 2012).

However, reports indicate that under water deficit conditions, the reduction in intercropped soybean yield is generally less pronounced than that observed in intercropped maize. This suggests that soybean exhibits greater drought tolerance and adaptive capacity, enabling it to maintain yield under limited water availability (Chen et al., 2024). Zhang et al. (2022) further reported that soybean in intercropping systems may respond to water stress by increasing root growth and plasticity, enhancing access to soil moisture. While this adaptive strategy may limit aboveground biomass accumulation, it reflects belowground niche differentiation and partial complementarity, allowing soybean to mitigate the negative effects of both drought stress and interspecific competition.

3.4 AVAILABLE SOIL NITROGEN CONTENTS UNDER THE SOLE MAIZE AND ITS INTERCROPPING SYSTEMS

Table 7 shows how soil nitrogen is affected by irrigation treatments and maize cropping patterns. The values of soil nitrogen under the investigated irrigation regimes in both growth seasons showed significant differences ($p < 0.05$), according to the results. While irrigation with water stress treatments decreased soil accessible nitrogen by 8 % and 16 % under irrigation with WS1 and WS2, respectively, on average during both growing seasons, irrigation with RI achieved the maximum value of soil available nitrogen. It has been noted that poor nodule development, shape, and function significantly lower nitrogen fixation in soybeans, when expose to water stress (Jumrani et al. 2024).

The findings also revealed that the soil nitrogen values under the maize cropping system varied significantly in both growing seasons ($p < 0.05$). Compared to sole maize, all maize intercropping systems had higher soil levels of accessible nitrogen. When 75 % soybean was intercropped with maize, the highest levels of soil accessible nitrogen were observed (Table 7). Since soybean fixes atmospheric nitrogen in the soil and makes it available to the companion crop, intercropping maize with soybean can improve maize's uptake of nitrogen due to maize's high nitrogen requirements (Nasar et al., 2023).

The findings in Table 7 also showed that, due to the residual effects of soybean, higher amounts of soil available nitrogen were observed during the second growing

Table 6. The yield of soybean (ton ha⁻¹) under different irrigation treatments and cropping systems (in both growing seasons).

Irrigation	cropping system	First growing season	Second growing season	Mean
RI	Sole soybean	3.20	3.32	3.26
	50 % soybean + 100 % maize	1.84	1.87	1.86
	65 % soybean + 100 % maize	2.24	2.33	2.29
	75 % soybean + 100 % maize	2.48	2.56	2.52
Mean		2.44	2.52	2.48
WS1	Sole soybean	3.02	3.16	3.09
	50 % soybean + 100 % maize	1.56	1.60	1.58
	65 % soybean + 100 % maize	1.81	1.90	1.86
	75 % soybean + 100 % maize	2.02	2.15	2.09
Mean		2.10	2.20	2.15
WS2	Sole soybean	2.82	2.82	2.82
	50 % soybean + 100 % maize	1.35	1.41	1.38
	65 % soybean + 100 % maize	1.56	1.60	1.58
	75 % soybean + 100 % maize	1.85	1.96	1.91
Mean		1.85	1.96	1.91
Mean (CS)	Sole soybean	2.95	3.10	3.03
	50 % soybean + 100 % maize	1.58	1.63	1.61
	65 % soybean + 100 % maize	1.87	1.96	1.92
	75 % soybean + 100 % maize	2.21	2.22	2.22
LSD _{0.05}				
IR		0.06	0.09	
CS		0.12	0.13	
IR × CS		ns	ns	

IR = irrigation treatments, CS = cropping systems, RI, WS₁, and WS₂ = irrigation with 120, 100, 80 % ETc, respectively, ns = not significant at $p \leq 0.05$, LSD values are presented only for factors with significant F-test.

season compared to the first. Because of their ability to fix atmospheric nitrogen through symbiotic relationships with root nodule bacteria, soybeans have a positive residual nitrogen effect on soil in succeeding seasons (Osunde et al., 2003). According to Zhang et al. (2024), soybeans improve soil health by increasing organic matter and possibly improving soil structure, which benefits subsequent crops indirectly.

In both growing seasons, there was no significant ($p > 0.05$) interaction between irrigation treatments and intercropping systems. In comparison to the values obtained for sole maize, irrigation with the RI increased soil accessible nitrogen by 30 %, 34 %, and 41 % in the first growing season and by 40 %, 46 %, and 50 % in the second season when soybean was intercropped with maize in 50 %, 65 %, and 75 %, respectively. Furthermore, the amount of accessible nitrogen in the soil dropped under both water stress conditions. In soybeans, water stress significantly affects nitrogen fixation, resulting in re-

duced activity and perhaps irreversible nodule damage (Basal & Szabó, 2020). It also reduces the activity of nitrogenase, an enzyme that helps fix nitrogen, and oxygen intake in nodules (Lumactud et al., 2022). The benefits of intercropping leguminous crops like soybean with maize in order to maintain a reasonable level of soil nitrogen under moderate water stress are highlighted by the fact that, in both water stress treatments, the soil available nitrogen levels under maize intercropping systems were higher than those recorded under sole maize cultivation during both growing seasons (Table 7).

3.5 AVAILABLE SOIL PHOSPHORUS CONTENTS UNDER THE SOLE MAIZE AND ITS INTER-CROPPING SYSTEMS

Phosphorus values under the investigated irrigation treatments, intercropping systems, and their interaction

Table 7: Available soil nitrogen (mg kg⁻¹) under irrigation treatments and maize cropping systems in both growing seasons.

Irrigation	cropping system	First growing season	Second growing season	Mean
RI	Sole maize	11.11	10.67	10.89
	50 % soybean + 100 % maize	14.01	14.25	14.13
	65 % soybean + 100 % maize	14.34	14.78	14.56
	75 % soybean + 100 % maize	14.88	15.00	14.94
Mean		13.58	13.68	13.63
WS1	Sole maize	9.81	9.67	9.74
	50 % soybean + 100 % maize	12.80	13.06	12.93
	65 % soybean + 100 % maize	13.24	13.68	13.46
	75 % soybean + 100 % maize	13.88	14.01	13.95
Mean		12.43	12.60	12.52
WS2	Sole maize	8.71	8.57	8.64
	50 % soybean + 100 % maize	11.80	12.05	11.93
	65 % soybean + 100 % maize	12.14	12.58	12.36
	75 % soybean + 100 % maize	12.88	13.01	12.95
Mean		11.38	11.55	11.47
Mean (CS)	Sole maize	9.87	9.36	9.62
	50 % soybean + 100 % maize	12.87	13.12	13.00
	65 % soybean + 100 % maize	13.24	13.68	13.46
	75 % soybean + 100 % maize	13.88	14.01	13.95
LSD _{0.05}				
IR		0.28	0.70	
CS		0.32	0.22	
IR × CS		ns	ns	

IR = irrigation treatments, CS = cropping systems, RI, WS₁, and WS₂ = irrigation with 120, 100, 80 % ETc, respectively, ns = not significant at $p \leq 0.05$, LSD values are presented only for factors with significant F-test.

in both growth seasons showed significant differences ($p < 0.05$), according to the results in Table 8.

Application of RI achieved the highest value of soil available phosphorus, while irrigation with water stress treatments decreased soil available phosphorus by 12 % and 25 % under irrigation with WS1 and WS2, respectively, averaged over both growing seasons (Table 8). These results were comparable to those for available soil nitrogen (Table 7). Water stress has been shown to dramatically lower soybeans' capacity to solubilize and absorb soil phosphorus. This is caused by a combination of detrimental physiological alterations in the plant that impair its phosphate acquisition processes and physical restrictions on phosphorus mobility in the soil (Salim et al., 2024). A severe or persistent water deficit overwhelms plants' attempts to compensate by changing root development and producing organic acids to solubilize phosphorus (Williams & de Vries 2020).

The findings also showed that, in comparison to

sole maize irrigated with the three irrigation regimes, the available soil phosphorus levels were higher in all maize intercropping systems. When 75 % soybean was intercropped with maize, the highest quantities of soil-accessible phosphorus were seen. In addition, when 50 %, 65 %, and 75 % of soybeans were intercropped with maize under irrigation with necessary irrigation, the percentage increase in available soil phosphorus was 14 %, 21 %, and 30 % in the first growing season, while it was 62 %, 71 %, and 83 % in the second growing season, respectively, in comparison to the values obtained for sole maize (Table 8). According to Wang et al. (2025), soybeans can increase the availability of phosphorus in the soil, especially when they are intercropped with other species that can increase the exudation of organic acids from their roots. Phosphorus that is attached to soil particles is made more soluble by these organic acids, increasing its availability for plant uptake. By encourag-

Table 8: Available soil phosphorus (mg kg⁻¹) under irrigation treatments and maize cropping systems in both growing seasons.

Irrigation	cropping system	First growing season	Second growing season	Mean
RI	Sole maize	4.24	3.34	3.79
	50 % soybean + 100 % maize	5.30	5.81	5.56
	65 % soybean + 100 % maize	5.65	6.14	5.90
	75 % soybean + 100 % maize	6.01	6.51	6.26
Mean		5.30	5.45	5.38
WS1	Sole maize	4.01	3.10	3.56
	50 % soybean + 100 % maize	4.41	4.90	4.66
	65 % soybean + 100 % maize	4.85	5.34	5.10
	75 % soybean + 100 % maize	5.31	5.81	5.56
Mean		4.64	4.79	4.72
WS2	Sole maize	3.76	2.86	3.31
	50 % soybean + 100 % maize	3.94	4.34	4.14
	65 % soybean + 100 % maize	4.04	4.45	4.25
	75 % soybean + 100 % maize	4.30	4.70	4.50
Mean		4.01	4.09	4.05
Mean (CS)	Sole maize	4.00	3.10	3.55
	50 % soybean + 100 % maize	4.55	5.02	4.79
	65 % soybean + 100 % maize	4.85	5.31	5.08
	75 % soybean + 100 % maize	5.21	5.67	5.44
LSD _{0.05}				
IR		0.18	0.05	
CS		0.19	0.08	
IR × CS		0.29	0.11	

IR = irrigation treatments, CS = cropping systems, RI, WS₁, and WS₂ = irrigation with 120, 100, 80 % ET_c, respectively, ns = not significant at $p \leq 0.05$, LSD values are presented only for factors with significant F-test.

ing the release of root-secreted acid phosphatases in the rhizosphere, soybeans in a maize-soybean intercropping system improve organic phosphorus hydrolysis (An et al., 2024).

Furthermore, greater levels of soil accessible phosphorus were observed in the second growing season as opposed to the first, which might be attributed to the residual impacts of soybean (Table 8). Soybeans can benefit future harvests by releasing phosphorus from their leftovers. This residual effect may result in higher yields the following growing season (Adeola et al., 2024). The results also showed that soil available phosphorus concentrations dropped under both water stress conditions. Water stress in soybean plants can have a major impact on phosphorus uptake and release, reducing root absorption and preventing phosphorus diffusion in the soil (Salim et al., 2024). Additionally, plants under water stress may produce less root exudates, such as carboxylates, which

are necessary for the solubilization and uptake of phosphorus from the soil (Feng et al., 2021). However, the benefits of soybean with maize were increased in both growing seasons when intercropping under both water stress treatments resulted in greater soil accessible phosphorus levels than those under sole maize (Table 8).

3.6 LAND EQUIVALENT RATIO (LER)

The values of LER_{total} in Table 9 showed significant variations ($p < 0.05$) for irrigation treatments alone, and there were no significant differences for intercropping systems or their interaction ($p > 0.05$) both growing seasons.

Table 9 showed that throughout both growing seasons, irrigation with RI produced the highest partial and total LER values, but water stress treatments caused these values to decrease. Chen et al. (2025) stated that irrigation has a major impact on both partial and total LER

Table 9: The land equivalent ratios (LER) as affected by the studied irrigation treatments and soybean-maize intercropping systems in both growing seasons.

IR	Intercropping system	First growing season			Second growing season		
		LER _{soybean}	LER _{maize}	LER _{total}	LER _{soybean}	LER _{maize}	LER _{total}
RI	50 % soybean + 100 % maize	0.57	0.96	- 1.53	0.56	0.98	1.55
	65 % soybean + 100 % maize	0.70	0.90	1.60	0.70	0.89	1.60
	75 % soybean + 100 % maize	0.78	0.83	1.61	0.77	0.84	1.61
	Mean	0.68	0.90	1.58	0.68	0.90	1.58
WS ₁	50 % soybean + 100 % maize	0.51	0.95	1.47	0.50	0.97	1.47
	65 % soybean + 100 % maize	0.60	0.86	1.46	0.60	0.87	1.47
	75 % soybean + 100 % maize	0.67	0.78	1.45	0.68	0.79	1.47
	Mean	0.59	0.86	1.46	0.59	0.87	1.47
WS ₂	50 % soybean + 100 % maize	0.51	0.92	1.44	0.50	0.96	1.45
	65 % soybean + 100 % maize	0.60	0.83	1.43	0.59	0.84	1.43
	75 % soybean + 100 % maize	0.70	0.72	1.42	0.69	0.73	1.43
	Mean	0.60	0.82	1.43	0.59	0.84	1.44
Mean (IS)	50 % soybean + 100 % maize	0.53	0.94	1.48	0.52	0.97	1.49
	65 % soybean + 100 % maize	0.63	0.86	1.50	0.63	0.87	1.50
	75 % soybean + 100 % maize	0.71	0.77	1.49	0.71	0.79	1.50
LSD _{0.05}							
IR				0.13	0.08		
IS				ns	ns		
IR × IS				ns	ns		

IR = irrigation treatments, CS = cropping systems, RI, WS₁, and WS₂ = irrigation with 120, 100, 80 % ETc, respectively, ns = not significant at $p \leq 0.05$, LSD values are presented only for factors with significant F-test.

in soybean-maize intercropping, with full or adequate irrigation typically increasing LER and declining under deficit irrigation. Additionally, the maximum partial LER values for maize were obtained at the lowest soybean planting density across all three irrigation treatments in both growing seasons, whereas the highest total LER was found in the intercropping of 65 % soybean with 100 % maize during both growing seasons, i.e., 1.50. The partial LER values for soybean increased with higher planting densities. On the other hand, intercropping 75 % soybean with 100 % maize while applying the required irrigation resulted in the highest total LER value, which was 1.61 for both growth seasons. This outcome suggested that this intercropping technique had a sizable yield benefit. Stated differently, if soybeans had been planted as mono crop, 61 % more area would have been needed to achieve the same yield as that intercropping system. According to Liu & Yang (2024), the LER value in a soybean-maize intercropping system is significantly influenced by the density of soybean plantings, indicating the productivity advantage of intercropping over sole cropping. When

combined with the optimal density of maize, increasing the density of soybeans can raise the LER value and perhaps increase the benefits of production (Chen et al., 2025).

Additionally, when water stress treatments were applied, the values of LER_{total} decreased as the planting density of soybeans increased. This suggests that there was more competition for water between the intercrops, which resulted in a lower yield for both intercrops. As a result, the highest value was achieved when 50 % soybean was intercropped with 100 % maize (Table 9). Higher intercropped soybean densities can increase competition with maize for resources such as sunshine, water, and nutrients, particularly beneath the canopy of the taller maize plants, according to Wang et al. (2023). Because both crops yielded more in the second season than in the first, the results likewise indicated greater values of LER_{soybean}, LER_{maize}, and LER_{total} in the second season. In Egypt, Rashwan & Zen El-Dein (2017), Abd-Rabboh et al. (2025), and Taha & Abdel-Wahab (2024) showed

similar LER values for both soybean and maize intercropping systems over a range of planting densities.

3.7 WATER EQUIVALENT RATIO (WER) AND CHANGE IN WATER USE (Δ WU)

Table 10 indicates significant variations ($p < 0.05$) in WER_{total} among irrigation regimes, with a fall in values corresponding to decreased applied irrigation water. The values of $WER_{soybean}$ and WER_{maize} exhibited a consistent trend over both growth seasons. The results are attributable to the diminished yield of intercropped soybean and maize under water stress treatments, with WER_{total} decreasing from 1.40 under irrigation with RI to 1.27 under irrigation with WS2, averaged across the two growing seasons. Reports indicate that WER demonstrates substantial improvements in water use efficiency compared to monocultures by employing complementary water absorption at varying soil depths and periods, hence minimizing water waste and enhancing total water productivity (Zhang et al., 2022).

Table 10 indicates that the WER_{total} values exhibited significant differences ($p < 0.05$) for maize intercropping systems across both growing seasons. The maximum $WER_{soybean}$ values were recorded at the highest soybean planting density, whereas the highest WER_{maize} and WER_{total} values were noted at the lowest soybean planting density during both growing seasons. The interaction between irrigation treatments and maize intercropping systems shown no significant variations ($p > 0.05$) in WER_{total} . The maximum $WER_{soybean}$ values across the three irrigation treatments were recorded when 75% soybean was intercropped with 100% maize in both growing seasons. The peak values of WER_{maize} and WER_{total} were recorded when 50 % soybean was intercropped with 100 % maize during both growth seasons. With irrigation using the RI, the peak values of WER_{total} were 1.41 and 1.42 in the first and second seasons, respectively. This figure indicates that the intercropping system can achieve a specified yield with reduced water usage compared to producing the same yield in individual monoculture fields, implying a 42 % enhancement in water use efficiency at the system level relative to monoculture. Reports suggest that in a soybean-maize intercropping system, soybean planting density significantly affects the water use efficiency ratio, which evaluates the water use efficiency of the intercropping system relative to sole cropping (Ren et al., 2016). Generally, higher soybean planting densities may diminish the WER for maize, however they can also augment the overall WER for the intercropping system, especially when densities are optimized for both crops (Raza et al., 2022).

Moreover, the application of water stress treatments

resulted in diminished partial and total WER values during both growing seasons. Ren et al. (2016) contended that the optimal soybean planting density in intercropping with maize under water scarcity is crucial for maximizing water use efficiency, as excessively high soybean densities may lead to increased resource competition and negatively impact yields. Reports indicate that maize and soybean have distinct water intake patterns at various growth stages, resulting in temporal complementarity in water utilization (Zhang et al., 2022). Consequently, intercropping can improve water usage efficiency for maize, particularly under conditions of moderate water stress (Liu et al., 2025). Water stress may exacerbate competition for water between maize and soybean, thereby advantaging maize because to its superior competitive capacity (Raza et al., 2021).

The partial and total values of WER were heightened during the second growing season compared to the first growing season. The increased WER_{total} in the second growing season, resulting from the residual effects of soybean on the soil, improved soil water retention, hence positively affecting the yield of intercropped maize (Table 10). Intercropping markedly enhances water use efficiency, affected by the planting density of the intercropping system, exhibiting a considerable water usage benefit as indicated by Mao et al. (2012).

Moreover, there were notable variations ($p < 0.05$) in the Δ WU values for irrigation treatments and maize intercropping systems across both growing seasons, as well as for the interaction between irrigation treatments and intercropping systems exclusively in the second growing season (Table 10). The findings indicated that irrigation with RI diminished the Δ WU value in comparison to irrigation under water stress conditions. The values of Δ WU were more negative under irrigation with RI than under water stress treatments, indicating a greater magnitude of the water-saving benefit with RI. This pattern was observed under irrigation treatments, intercropping systems, and their interaction. This suggests that the system demonstrated greater efficiency in water conservation (compared to sole crops) during periods of ample water availability, or that sole crops consumed much more water under full irrigation than intercrops (Mao et al., 2012). Additionally, all examined intercropping systems attained total WER values surpassing 1 and Δ WU values below 0, signifying improved water use efficiency (Table 8). Similar WER and Δ WU values were documented in Egypt by Ouda & Zohry (2023) for sugar beet intercropping systems with legumes, and by Zohry & Ouda (2025) for wheat intercropping systems with leguminous crops.

Studies suggest that the extensive root system of soybeans can penetrate compacted soil layers, improving

Table 10: Water equivalent ratio (WER) and change in water use (Δ WU) under irrigation treatments and maize intercropping systems in both growing seasons.

IR	IS	First growing season				Second growing season			
		WER _{soybean}	WER _{maize}	WER _{total}	Δ WU (%)	WER _{soybean}	WER _{maize}	WER _{total}	Δ WU (%)
RI	IS ₁	0.42	0.98	1.41	-0.21	0.43	0.99	1.42	-0.22
	IS ₂	0.50	0.89	1.40	-0.20	0.51	0.90	1.41	-0.20
	IS ₃	0.54	0.84	1.38	-0.19	0.55	0.84	1.39	-0.18
Mean		0.48	0.90	1.39	-0.20	0.49	0.91	1.40	-0.20
WS ₁	IS ₁	0.36	0.97	1.33	-0.16	0.37	0.96	1.34	-0.17
	IS ₂	0.40	0.86	1.27	-0.13	0.43	0.86	1.30	-0.14
	IS ₃	0.44	0.78	1.22	-0.10	0.47	0.78	1.26	-0.11
Mean		0.40	0.87	1.27	-0.13	0.42	0.87	1.30	-0.14
WS ₂	IS ₁	0.37	0.95	1.33	-0.11	0.37	0.96	1.34	-0.18
	IS ₂	0.42	0.84	1.26	-0.11	0.43	0.84	1.27	-0.11
	IS ₃	0.49	0.73	1.21	-0.07	0.49	0.73	1.23	-0.08
Mean		0.43	0.84	1.27	-0.10	0.43	0.84	1.28	-0.12
Mean (IS)	IS ₁	0.38	0.97	1.35	-0.16	0.39	0.97	1.36	-0.19
	IS ₂	0.44	0.86	1.31	-0.14	0.46	0.87	1.33	-0.15
	IS ₃	0.49	0.79	1.28	-0.12	0.50	0.78	1.29	-0.12
LSD _{0.05}									
IR				0.06	-0.04				
IS				0.03	-0.03				
IR $\times$ IS				ns	ns				

IR = irrigation systems, IS = intercropping systems, RI, WS₁, and WS₂ = irrigation with 120, 100, 80 % ETc, respectively, IS1 = 50 % soybean + 100 % maize, IS2 = 65 % soybean + 100 % maize, IS3 = 75 % soybean + 100 % maize, ns = not significant at $p \leq 0.05$, LSD values are presented only for factors with significant F-test.

water penetration and drainage, hence augmenting water use efficiency (Ferreira et al., 2023). Furthermore, in a soybean-maize intercropping system, soybean planting density significantly impacts water use by altering root distribution, resource competition, and overall water absorption patterns (Zhang et al., 2022). Accordingly, intercropping can enhance water use efficiency by 4 % to 99 % compared to monoculture, especially when water availability is not limited (Mao et al., 2012). The root system plays a crucial role in water acquisition in intercrops, as species mixtures have been shown to increase root length density, hence decreasing water loss through evaporation (Pankou et al., 2021).

3.8 TOTAL INCOME (TI) AND MONETARY ADVANTAGE INDEX (MAI)

Table 11 exhibited heightened TI values for all assessed intercropping systems relative to maize monoculture, with the highest values attained by intercropping

75 % soybean with 100 % maize across the three irrigation regimes in both growth seasons. This signifies that the combined yield and income from the intercropping system exceed the overall yields and incomes from producing the two crops separately.

Consequently, heightened positive values of MAI were attained in the three analyzed intercropping systems, signifying distinct yield and economic advantages over maize monoculture. The MAI values were the highest for the intercropping of 75 % soybean with 100 % maize in both growth seasons, signifying the most advantageous economic combination among the assessed intercropping systems (Table 11).

These findings correspond with those of LER, where Dhima et al. (2007) demonstrated that the greatest LER values in an intercropping system yield economic benefits evident in MAI values. The outcomes can be ascribed to enhanced overall productivity in intercropping with somewhat reduced input investment (Banik et al., 2006).

Table 11: 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 ⁻¹)	MAI	TI (USD ha ⁻¹)	MAI	TI (USD ha ⁻¹)	MAI
First growing season						
Sole maize	1,168	--	1,057	--	952	--
50 % soybean + 100 % maize	2,606	914	2,262	723	2,019	617
65 % soybean + 100 % maize	2,850	1,069	2,370	747	2,093	629
75 % soybean + 100 % maize	2,965	1,123	2,448	760	2,214	655
Second growing season						
Sole maize	2,095	--	1,930	--	1,836	--
50 % soybean + 100 % maize	3,387	1,202	3,007	961	2,752	854
65 % soybean + 100 % maize	3,527	1,323	3,033	970	2,721	818
75 % soybean + 100 % maize	3,579	1,356	3,043	973	2,741	824

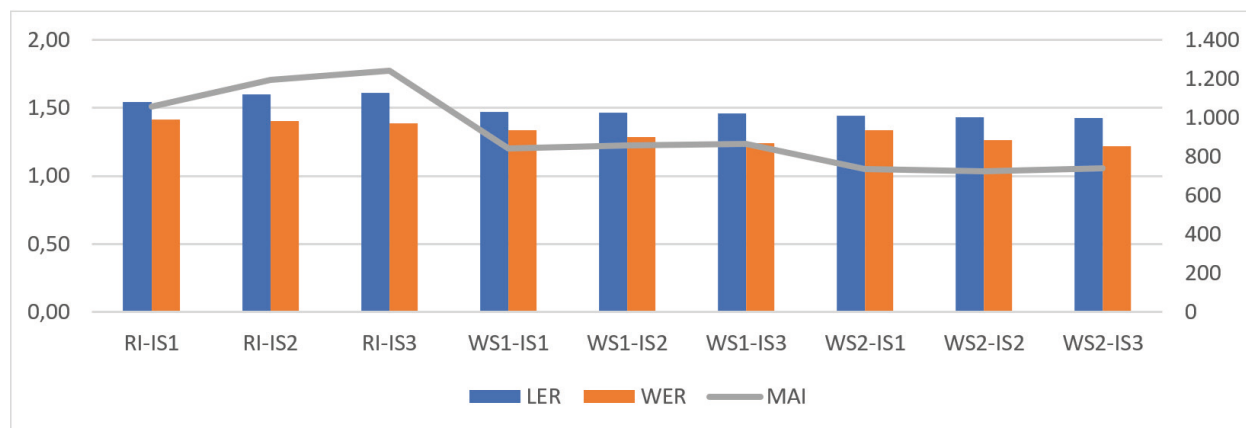
RI, WS₁, and WS₂ = irrigation with 120, 100, 80 % ETc, respectively.

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

Figure 9 provides a comparative graphical summary of the performance of the evaluated soybean-maize intercropping systems across irrigation regimes using three dimensionless, standardized indices: land equivalent ratio (LER), water equivalent ratio (WER), and monetary advantage index (MAI). LER and WER are presented as bars, whereas MAI is presented as a line, to distinguish

between the productivity and resource-use efficiency indices and the economic indicator. Each bar or line point represents the value of the corresponding index for a given intercropping-irrigation combination, allowing visual comparison of treatment effects on overall system performance. Because LER, WER, and MAI are derived indices expressed on a common, unit-free scale, they can be presented together without implying direct comparison of dissimilar response variables.

LER and WER quantify the biological productiv-

Figure 9: Graphical summary of the performance of the evaluated intercropping systems across irrigation regimes averaged over the two growing seasons.

RI-IS1 = required irrigation applied to 50 % soybean + 100 % maize, RI-IS2 = required irrigation applied to 65 % soybean + 100 % maize, RI-IS3 = required irrigation applied to 75 % soybean + 100 % maize, WS1-IS1 = irrigation with 100 % ETc applied to 50 % soybean + 100 % maize, WS1-IS2 = irrigation with 100 % ETc applied to 65 % soybean + 100 % maize, WS1-IS3 = irrigation with 100 % ETc applied to 75 % soybean + 100 % maize, WS2-IS1 = irrigation with 80 % ETc applied to 50 % soybean + 100 % maize, WS2-IS2 = irrigation with 80 % ETc applied to 65 % soybean + 100 % maize, WS2-IS3 = irrigation with 80 % ETc applied to 75 % soybean + 100 % maize.

ity and water-use efficiency advantages of intercropping relative to sole maize, whereas MAI reflects the associated economic benefit. Presenting these indices together therefore provides an integrated assessment of productivity, resource-use efficiency, and profitability, rather than three independent response variables. Variation among intercropping systems and irrigation regimes illustrates how overall system performance responds to water availability, enabling a visual evaluation of trade-offs and synergies among the evaluated systems.

4 CONCLUSION

The soybean–maize intercropping system evaluated under the sandy soils of Middle Egypt substantially improved land-use efficiency (75 % soybean + 100 % maize), water-use efficiency (50 % soybean + 100 % maize), and soil fertility (75 % soybean + 100 % maize) compared with sole maize cropping. Increasing soybean density enhanced total system productivity, nutrient enrichment, and economic returns; however, this occurred at the expense of a modest reduction in maize yield, which could be due to increased interspecific competition. A clear trade-off between land-use efficiency and water-use efficiency was observed, as intercropping 75 % soybean with 100 % maize maximized land-use and economic indicators (LER and MAI), whereas intercropping 50 % soybean with 100 % maize achieved the highest water-use efficiency (WER). These results indicate that optimal intercropping configurations depend on whether land productivity or water conservation is the primary management objective. Intercropping also mitigated the negative effects of water stress through complementary resource use, supporting its potential as a climate-resilient strategy for water-limited systems.

However, these findings are conditioned by the sandy soil texture and hot climatic conditions of the experimental site, which influence crop water demand, nutrient dynamics, and competitive interactions. Therefore, while the underlying mechanisms are broadly relevant, the quantitative outcomes may vary under different soil types, climatic regimes, and management practices, thus site-specific optimization is recommended.

Furthermore, in line with FAO dryland agriculture frameworks, the results indicate that optimizing legume planting density in maize-based intercropping systems can enhance water productivity and soil quality while improving yield stability across seasons with contrasting water availability. The consistent performance of the intercropping systems across the two growing seasons and irrigation regimes suggests reduced sensitivity to season-

al variability, supporting their potential as a scalable and climate-resilient strategy for dryland farming systems.

Data Availability Statement

The datasets generated and analyzed during the current study are available in the Zenodo repository at <https://doi.org/10.5281/zenodo.18467816>.

5 REFERENCES

- Abd-Rabboh, A. M. K., Awad M.M., Mohamed, M.K.A., Saleh, H.A.M.A. & Ghazy N. A. (2025). Effect of compost tea application on disease incidence and productivity of intercropping maize and soybean. *Middle East Journal of Agriculture Research*, 14(02), 284-299.
- Abou-Elela, A. M. (2012). Effect of irrigation treatments of yield and quality on soybean and maize grown under different intercropping patterns. *Journal of Plant Production*, 3(11), 2843–2856.
- Adeola, R.O., Akinrinola, T.B., Fagbola, O. (2024). Maize and soybean response to the residual influence of early-season cropping system and fertilizer applications. *Chilean Journal of Agriculture and Animal Science, ex Agro-Ciencia*, 40(1), 33-43.
- Ahmad, M., Zhao, T., Gitari, H., Zhao, H., & Tang, L. (2025). Long-term year-interval effect of continuous maize/soybean intercropping on maize yield and phosphorus use efficiency. *Plants*, 14(7), 1060. <https://doi.org/10.3390/plants14071060>.
- Allen R.G, Pereira, L.S, Raes, D., Smith M. (1998). *Crop evapotranspiration: Guideline for computing crop water requirements*. FAO No56. pp 109-158.
- An, R., Yu, R.P., Xing, Y., Zhang, J-D, Bao, X-G, Lambers, H., Li, L. (2024). Intercropping efficiently utilizes phosphorus resource in soil via different strategies mediated by crop traits and species combination. *Plant Soil*, 497, 705–725. <https://doi.org/10.1007/s11104-023-06426-4>.
- Atia, R. H., Metwally, M. A., El-Atawy, G. S. (2012). Effect of irrigation water amounts and nitrogen rates on optimum maize yield and net return under drip irrigation system at Northwest Delta, Egypt. *Journal of Soil Sciences and Agricultural Engineering*, 3(5): 549-559. doi: 10.21608/js-sae.2012.54326.
- 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.
- Basal, O., & Szabó, A. (2020). The combined effect of drought stress and nitrogen fertilization on soybean. *Agronomy*, 10, 384. <https://doi.org/10.3390/agronomy10030384>.
- Chen, P., Xian, G., Pu, T., Wanzhuo, G., Jianzheng, L., Yushan, W. (2025). Soybean-maize intercropping combined with water management enhances leaf traits to obtain yield benefits in semi-arid regions, *Field Crops Research*, 327. 109869. <https://doi.org/10.1016/j.fcr.2025.109869>.
- Chen, P., Zheng, B., Yang, H., Du, Q., Fu, Z., Yang, W. (2024). Relay intercropping boosts soybean recovery growth and delays nodule senescence to achieve yield advantages, *Ag-*

- riculture, *Ecosystems & Environment*, 369, 109030. <https://doi.org/10.1016/j.agee.2024.109030>.
- 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.
- El-Sherif, A.M.A. & Ali, M.M. (2015) Effect of deficit irrigation and soybean/maize intercropping on yield and water use efficiency. *International Journal of Current Microbiology Application Science*, 4(12), 777-794.
- Ennin, S.A., & Clegg, M.D. (2001). Effect of soybean plant populations in a soybean and maize rotation. *Agronomy Journal*, 93(2), 396-403. <https://doi.org/10.2134/agronj2001.932396x>.
- Federer, W.T. (2012). *Statistical Design and Analysis for Intercropping Experiments*. Vol. 1: Two crops. Springer Series in Statistics. Springer-Verlag, New York, USA.
- Feng, Y. Y. He, J., Turner, N.C., Siddique, K.H.M., Li, F. M. (2021). Phosphorus supply increases internode length and leaf characteristics, and increases dry matter accumulation and seed yield in soybean under water deficit. *Agronomy*, 11,930. <https://doi.org/10.3390/agronomy11050930>.
- Ferreira, C.J.B., da Silva, A.G., de Oliveira P.V.R., Tormena, C.A., Braz, G.B.P., de Freitas S. M., da Silva, A.L.B.R. (2023). Effects of second-season crops on soybean cultivation in compacted soil in Brazilian cerrado. *Agronomy*, 13, 79. <https://doi.org/10.3390/agronomy13010079>.
- 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.
- Gomez, K.A., & Gomez A.A. (1984). *Statistical Procedures for Agricultural Research*. 2nd ed. John Wiley and Sons, Inc. New York. pp 22-67.
- He, H., Yang, L., Fan, L., Zhao, L., Wu, H., Li, C. (2011). The effect of intercropping of maize and soybean on microclimate. *5th Computer and Computing Technologies in Agriculture (CCTA)*, Beijing, China. pp. 257-263, [ff10.1007/978-3-642-27278-3_27](https://doi.org/10.1007/978-3-642-27278-3_27). [ffhal-01360987f](https://doi.org/10.1007/978-3-642-27278-3_27).
- Hesse, P. R. A. (1971). *Text Book of Soil Chemical Analysis*. Juan Murry (Publisher) Ltd., London. pp 27-45.
- Israelsen O.W., & Hansen V.E. (1962). *Irrigation Principles and Practices*. 3rd Edition, Wiley International Edition, New York.
- Jackson, M.L. (1973). *Soil chemical analysis*. Prentice-Hall, Inc., Englewood Cliffs, NJ, USA.
- Jumrani, K., Bhatia, V.S., Kataria, S. et al. (2024). The interactive effect of high temperature and water deficit stress on nitrogen fixation, photosynthesis, chlorophyll fluorescence, seed yield and quality in soybean (*Glycine max*). *Plant Physiology*, 29, 125–140. <https://doi.org/10.1007/s40502-023-00763-3>
- Klimek-Kopyra, A., Baciór, M., Lorenc-Kozik, A., Neugschwandtner, R.W., Zajac T (2021). Intraspecific competition as a driver for true production potential of soybean. *Italian Journal of Agronomy*, 16(1), 1709. <https://doi.org/10.4081/ija.2020.1709>.
- Klute A. (1986). *Methods of Soil Analysis, Part I. Physical and Mineralogical Method*. American Society of Agronomy. 1986. Madison. Wisconsin. USA.
- Kubota, A., Safina, S.A., Sheb, S.M., Mohamed, A.E., Ishikawa, N., | Maruyama, S. (2015). Evaluation of intercropping system of maize and leguminous crops in the Nile Delta of Egypt. *Tropical Agriculture and Development*, 59(1), 1419.
- Li, L., Tilman, D., Lambers, H., & Zhang, F. (2014). Plant diversity and overyielding: Insights from belowground facilitation of intercropping in agriculture. *New Phytologist*, 203, 63–69.
- Li, G., Liang, Y., Liu, Q., Zeng, J., Ren, Q., Guo, J., Xiong, F. and Lu, D. (2024). Enhancing production efficiency through optimizing plant density in maize–soybean strip intercropping. *Frontiers of Plant Science*, 15, 1473786. doi: 10.3389/fpls.2024.1473786.
- Lithourgidis, A., Dordas, C., Damalas, C.A., Vlachostergios, D. (2011). Annual intercrops: an alternative pathway for sustainable agriculture. *Australian Journal of Crop Science* 5(4), 396-410.
- Liu, H., Gao, X., Li, C., Cai, Y., Song, X., Zhao, X. (2025). Intercropping increases plant water availability and water use efficiency: A synthesis. *Agriculture, Ecosystems & Environment*, 379, 109360. <https://doi.org/10.1016/j.agee.2024.109360>.
- Liu, J., & Yang, W. (2024). Soybean maize strip intercropping: A solution for maintaining food security in China, *Journal of Integrative Agriculture*, 23(7), 2503-2506. <https://doi.org/10.1016/j.jia.2024.02.001>.
- Liu, M. & Zhao H. (2023). Maize-soybean intercropping improved maize growth traits by increasing soil nutrients and reducing plant pathogen abundance. *Frontiers in Microbiology*, 14, 1290825. doi: 10.3389/fmicb.2023.1290825.
- Lumactud R.A., Dollete, D., Liyanage, D.K., Szczygłowski, K.,....., Thilakarathna, M. S. (2022). The effect of drought stress on nodulation, plant growth, and nitrogen fixation in soybean during early plant growth. *Journal of Agronomy and Crop Science*, 209(3), 345-354. <https://doi.org/10.1111/jac.12627>.
- Mead, R. & R.W. Willey, 1980. The concept of a “land equivalent ratio” and advantages in yields from intercropping. *Exper. Agric.*, 16: 217- 228.
- Mangena, P. (2018). Water Stress: Morphological and Anatomical Changes in Soybean (*Glycine max* L.) Plants. In: *Plant, Abiotic Stress and Responses to Climate Change*. In:TechOpen; Available from: <http://dx.doi.org/10.5772/intechopen.72899>.
- Mao, L.L., Zhang, L.Z., Li, W.W., Werf, W.V.D., Sun, J.H., Spieritz 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.
- Metwally, A. A., Safina, S. A., EL-Killany, R., Saleh, N. E. (2017). Growing corn and soybean in solid and intercropping systems under different levels of irrigation water. *Bioscience Research*, 14(3):532-541.
- Metwally, A. A., Safina, S. A., Saleh, N.A., Hefny, Y.A.A. (2023). Productivity of solid and intercropped soybean with corn

- under low irrigation water levels. *The Egyptian Journal of Agricultural Research*, 101(3), 897-913.
- Morris, R.A., & Garrity D.P. (1993). Resource capture and utilization in intercropping: Water. *Field Crops Research*, 34, 303-317.
- Morsy, A. R.; A. M. Mohamed; Abo-Marzoka E. A. & Megahed M. A. H. (2018). Effect of water deficit on growth, yield and quality of soybean seed. *Journal of Plant Production, Mansoura University*, 9(8), 709-716.
- Nasar, J., Khan, W., Khan, M. Z., Gitari, H. I., Gbolayori, J. F., Moussa, A. A., Hasan, M. (2021). Photosynthetic activities and photosynthetic nitrogen use efficiency of maize crop under different planting patterns and nitrogen fertilization. *Journal of Soil Science and Plant Nutrition*, 21, 2274-2284. doi: 10.1007/s42729-021-00520-1.
- Nasar, J., Zhao, C.J., Khan, R., Gul, H., Gitari, H., Shao, Z., Abbas, G., Haider, I., Iqbal, Z., Ahmed, W., Rehman, R., Liang, Q.P., Zhou, X.B., Yang, J. (2023). Maize-soybean intercropping at optimal N fertilization increases the N uptake, N yield and N use efficiency of maize crop by regulating the N assimilatory enzymes. *Frontiers of Plant Science*, 13, 1077948. doi: 10.3389/fpls.2022.1077948.
- Naser, M., Abdelghany, A.M., Wu, T., Tian F. (2024). Soybean in Egypt: current situation, challenges, and future perspectives. *Discover Sustainability*, 5, 425. <https://doi.org/10.1007/s43621-024-00656-x>.
- Osunde, A.O., Bala, A., Gwam, M.S, Tsado, P.A., Sanginga, N., Okogun, J.A. (2003). Residual benefits of promiscuous soybean to maize (*Zea mays* L.) grown on farmers' fields around Minna in the southern Guinea savanna zone of Nigeria, *Agriculture, Ecosystems & Environment*, 100(2-3), 209-220. [https://doi.org/10.1016/S0167-8809\(03\)00197-X](https://doi.org/10.1016/S0167-8809(03)00197-X).
- Ouda, S. & Zohry, A. (2023). Increasing sustainability by intercropping legume crops with sugar beet under imposed water stress. *Irrigation and Drainage*, 1-26. <https://doi.org/10.1002/ird.2884>.
- Ouda, S. & Zohry, A (2025). Dataset for soybean-maize intercropping under different irrigation regimes and soybean planting densities in Egypt. Zenodo. <https://doi.org/10.5281/zenodo.18467816>.
- 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(2), 283. <https://doi.org/10.3390/agronomy11020283>.
- Rao, M.R., & Willey, R.W. (1980). Evaluation of yield stability in intercropping: studies on sorghum/pigeon pea. *Experimental Agriculture*, 16(2), 105-116.
- Rashwan, E.A. & Zen El-Dein A.A. (2017). Effect of two patterns of intercropping soybean with maize on yield and its components under different nitrogen fertilizer levels. *Egyptian Journal of Agronomy*, 39(3), 449 - 466.
- Raza, M.A., Gul, H., Wang, J., Yasin, H.S., Qin, R., Bin Khalid, M.H., Naeem, M., Yang, W. (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, <https://doi.org/10.1016/j.jclepro.2021.127282>.
- Raza, M.A., Yasin, H.S., Gul, H., Qin, R., Mohi Ud Din, A., Khalid, M.H.B., Hussain, S., Gitari, H., Saeed, A., Wang, J., ..., Yang W (2022). Maize/soybean strip intercropping produces higher crop yields and saves water under semi-arid conditions. *Frontiers of Plant Science*, 13, 1006720. doi: 10.3389/fpls.2022.1006720.
- Ren, Y., Wang, J.L.Z., Zhang, S. (2016). Planting density and sowing proportions of maize-soybean intercrops affected competitive interactions and water-use efficiencies on the Loess Plateau, China, *European Journal of Agronomy*, 72, 70-79.
- 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.
- Sah, R.P., Chakraborty, M., Prasad, K. et al. (2020) Impact of water deficit stress in maize: Phenology and yield components. *Scientific Reports*, 10, 2944. <https://doi.org/10.1038/s41598-020-59689-7>.
- Salim, M., Chen, Y., Solaiman, Z.M. et al. (2024). Phosphorus fertilization differentially affects morpho-physiological traits and yield in soybean exposed to water stress. *Plant Soil*, 504, 779-797. <https://doi.org/10.1007/s11104-024-06657-z>.
- Taha A. M. & Kasem E. (2022). Water management of maize-cowpea intercropping system under surface irrigation. *Moroccan Journal of Agricultural Science*, 3(1), 29-38.
- Taha, A.M. & Abdel-Wahab, E.I. (2024). Water used by soybean and maize intercropping patterns as affected by different soybean cultivars and plant population. *Soils and Crops* 34(1), 29-39.
- Tan, K.H. (1996). *Soil Sampling, Preparation and Analysis*. Marcel Dekker, Inc. New York. p. 391.
- 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, L., Chen, X., Cheng, B., Yang, H., Gao, Y., Li, X., & Yang, W. (2025). Stage-specific phosphorus mobilization enhances phosphorus uptake in relay-intercropped soybean, *Agriculture, Ecosystems & Environment*, 388, 109660. <https://doi.org/10.1016/j.agee.2025.109660>.
- Wang, L., Cheng, B., Zhou, T., Jing, S., Liu, R., Gao, Y., Deng, C., Ye, W., Luo, Z., Raza, A., Xu, M., Wang, W., Liu, W., Yang, W. (2023). Quantifying the effects of plant density on soybean lodging resistance and growth dynamics in maize-soybean strip intercropping. *Frontiers in Plant Science*, 14, 1264378. doi: 10.3389/fpls.2023.1264378.
- Wang, W., Li, M-Y., Gong, D-S., Zhou, R., Khan, A., Zhu, Y. (2022). Water use of intercropped species: Maize-soybean, soybean-wheat and wheat-maize, *Agricultural Water Management*, 269, 107690, <https://doi.org/10.1016/j.agwat.2022.107690>.
- Wang, X., Wu, Z., Zhou, Q., Wang, X., Song, S., Dong, S. (2022) Physiological Response of Soybean Plants to Water Deficit. *Front. Plant Sci.* 12:809692. doi: 10.3389/fpls.2021.809692.
- Wang, Z., Wu, P., Zhao, X., Gao, Y., Chen, X. (2015). Water use and crop coefficient of the wheat-maize strip intercropping system for an arid region in northwestern China,

- Agricultural Water Management*, 161: 77-85. <https://doi.org/10.1016/j.agwat.2015.07.012>.
- 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 Agroecosystems; Elsevier BV: Amsterdam, The Netherlands, pp. 127–150.
- Williams, A., & de Vries, F.T. (2020) Plant root exudation under drought: implications for ecosystem functioning. *New Phytol* 225(5):1899–1905.
- WORLD-GRAIN.com (2024). <https://www.world-grain.com/articles/19851-egypt-to-import-more-soybeans>.
- WORLD-GRAIN.com (2025) <https://www.world-grain.com/articles/21288-egypts-soybean-imports-on-rise#:~:text=Egypt%20is%20forecast%20to%20produce,an%20annual%20increase%20of%203.1%25>.
- Yang, S., Zhao, Y., Xu, Y., Cui, J., Li, T., Hu, Y., , Chen Y. (2024). Yield performance response to field configuration of maize and soybean intercropping in China: A meta-analysis, *Field Crops Research*, 306, 109235, <https://doi.org/10.1016/j.fcr.2023.109235>.
- Zhang, W., Lu, J-S., Bai, J., Khan, A., Liu, S-T., Xiong Y-C. (2024). Introduction of soybean into maize field reduces N₂O emission intensity via optimizing nitrogen source utilization, *Journal of Cleaner Production*, 442, 141052, <https://doi.org/10.1016/j.jclepro.2024.141052>.
- Zhang, Y., Sun, Z., Su, Z., Du, J., Bai, W., Wang, Q., Wang, R., , Zhang, L. (2022). Root plasticity and interspecific complementarity improve yields and water use efficiency of maize/soybean intercropping in a water-limited condition, *Field Crops Research*, 282, 108523, <https://doi.org/10.1016/j.fcr.2022.108523>.
- Zhou, L., Su, L., Zhao, H., Zhao, T., Zheng, Y., Tang, L. (2024). Maize/soybean intercropping improves yield stability and sustainability in red soil under different phosphate application rates in southwest China. *Agronomy*, 14, 1222. <https://doi.org/10.3390/agronomy14061222>.
- Zohry, A. and Ouda, S. (2025). Legume crops enhance water use efficiency under intercropping system with wheat. *Moroccan. Journal. Of Agricultural Science* . 6 (3): 145-160.