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Improving Light Use, Pest Control, and Water Efficiency in Soybean-Maize Intercropping in Different Climates

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Abstract

Background

The article draws attention to the growing difficulties facing agriculture in water-scarce and climate-affected regions like the Mediterranean and MENA. In order to improve production and save resources, it highlights the significance of sustainable intensification through diverse cropping systems like cereal-legume intercropping. With an emphasis on genotype × environment interactions and microclimate modifications that can support sustainable food production, the study focuses on the potential of soybean-maize intercropping, especially using shade-tolerant soybean cultivars, to optimize light use, pest control, and water efficiency across contrasting climates.

Results

Mixed intercropping with shade-adapted Giza 111 achieved the highest land equivalent ratio (LER = 1.73), light use efficiency (LUE = 1.89 g/MJ), and net economic returns while suppressing aphids and soybean mosaic virus incidence. Pearson correlations revealed strong negative relationships between LER and pest populations ($r = -0.914$, $p < 0.001$) and positive associations with water consumption, highlighting arid-environment trade-offs. Multiple regression models (R^2=0.918–0.941) successfully predicted yield from light, pest, and water variables. Cross-climatic validation confirmed conserved light-productivity relationships but divergent water-productivity dynamics between irrigated Mediterranean and rainfed temperate systems. Shade-tolerant cultivars enhanced associational tolerance mechanisms, reducing pest pressure by > 40% through microclimate modification.

Conclusions

We propose a scalable conceptual framework for soybean-maize intercropping across MENA regions, emphasizing genotype selection, spatial arrangement optimization, and integrated pest management to promote sustainable food production in water-scarce agro-ecosystems. With respect to Poland's temperate climate, this study will contribute significantly to developing a model development across contrasting climatic zones.

1 Introduction

Climate change, water scarcity, and population growth are intensifying food security challenges across the Mediterranean and Middle East and North Africa (MENA) regions (Gleick, 2014; Misra, 2014; Waha et al., 2017; World Bank, 2017 and 2021; Iraqi and Abdallah, 2022; Mohammed Qasem and Scholz, 2025; Zohry and Ouda, 2025a). Sustainable intensification through diversified cropping systems offers pathways to enhance productivity while conserving natural resources in water-scarce Mediterranean and MENA regions (Yilmaz et al., 2008; Keshyagol et al., 2026; Wang et al., 2026). Despite the benefits demonstrated by cereal-legume intercropping, critical gaps remain in understanding how genotype × system interactions influence light harvesting, pest and disease dynamics, and water use across diverse climates. This study focuses on the shade-tolerant soybean cultivar Giza 111 (*Glycine max* L.), quantifying the impact of light microclimates it develops on suppressing vector-borne diseases such as Soybean Mosaic Virus (SMV), linking "associational tolerance" to light attenuation levels (Abdel-Wahab et al., 2025a; Abdel-Wahab et al., 2025b). Additionally, the study develops predictive regression models integrating light use efficiency (LUE), pest dynamics, and water consumption, offering a scalable framework for climate-smart intensification. Giza 111 is highlighted not only for its yield but also for maintaining high efficiency under significant light attenuation, serving as a benchmark cultivar for breeding in water-scarce areas (Liu et al., 2020; Abdel-Wahab et al., 2025a). Previous research has shown improvements in LUE and land equivalent ratio (LER) in shade-adapted cultivars under intercropping, but this study uniquely integrates detailed genotype × system interactions across contrasting Mediterranean and temperate European climates (El Ansari et al., 2023; Scordia et al., 2024; Abdel-Wahab et al., 2025b). Poland's agricultural geography offers a wide variety of pests and diseases, which makes it an ideal setting for researching how sustainable agriculture can help reduce these problems through microclimate adjustment (Zieliński et al., 2025). Poland is a perfect place to research how shade-adapted cultivars affect soybean yield because of its moderate environment and fluctuating sunshine levels (Kaliska et al., 2025). By selecting environments with fundamentally different limiting factors (Egypt: water limitation; Poland: temperature and photoperiod limitation), we can rigorously test whether core mechanisms such as LUE and associated resistance are generalizable, thereby providing broader guidance for intercropping design across global agroecological zones (Moore et al., 2022; Abdel-Galil et al., 2025). This cross-climatic approach leverages actual field data from Egypt and model forecasts for Poland to offer a scalable, region-specific strategy for optimizing soybean-maize intercropping systems under diverse environmental conditions. The study of Poland's temperate, rainfed environment will contribute significantly to predictive model development for MENA agro-ecosystems by enabling cross-climatic validation of intercropping mechanisms. Previous research in Poland has demonstrated the potential for successful intercropping of leguminous crops with cereals for both whole-crop biomass and grain production (Sowiński, 2014, 2024). In Polish climatic conditions, soybean sowing typically occurs in early May, which is slightly later than other legumes sown in March or early April, yet this small delay does not significantly affect yield except for winter varieties (Serafin-Andrzejewska et al., 2021; Prusiński et al., 2016). The climate in Poland, particularly in the province of Wielkopolska—one of the warmest regions—is suitable for maize cropping from May to September, aligning closely with maize planting dates in MENA countries and indicating maize's adaptability to diverse climates (Bernacki, 2018). Although frost stress currently limits maize cultivation suitability, climate change projections suggest a decrease in frost risk, potentially expanding favorable areas for maize production to over 50% of Poland by the 2080s (Król-Badziak et al., 2024). This evolving temperate environment, combined with moderate temperatures and rainfall, provides an excellent model for studying and applying soybean-maize intercropping in MENA regions, where water scarcity and climatic variability challenge sustainable production. Poland's climatic parallels and future projections make it an ideal reference for optimizing intercropping systems that maximize yield, resource use efficiency, and resilience in water-limited Mediterranean and MENA agroecosystems. To address these challenges, this study: (1) assesses four Egyptian soybean cultivars with differing architectural and physiological characteristics under four spatial arrangements; (2) quantifies correlations between light parameters, water consumption (WCU), pest pressure, and yield; and (3) develops predictive models to guide system optimization for MENA conditions (Abdel-Wahab et al., 2019a; Metwally

et al., 2021). Our hypotheses are: (i) shade-adapted cultivars in mixed intercropping will maximize LUE and LER; (ii) intercropping will decrease disease incidence and pest populations through microclimate modification; and (iii) integrated light-pest-water models will enable yield prediction under resource-limited conditions. This study includes assessments of soil microbial communities, specifically populations of nitrogen-fixing bacteria such as *Azotobacter* sp. and *Rhizobia* sp., along with nematode populations. These belowground biotic factors are integral to understanding the full suite of ecosystem services that intercropping can enhance. Beneficial soil microbes contribute to improved nutrient cycling and availability, which can support higher light use efficiency and crop productivity, directly linking to the hypothesis that shade-adapted cultivars will maximize system efficiency (Hypothesis i). Meanwhile, nematodes, particularly parasitic species, can influence root health and plant vigor, intersecting with pest dynamics and disease incidence addressed by the hypothesis that intercropping will reduce pest populations through microclimate and biological interactions (Hypothesis ii). Incorporating soil biotic data allows for a more holistic analysis of resource complementarity and pest suppression mechanisms within the intercropping system. Furthermore, these measurements enrich the integrated light-pest-water models (Hypothesis iii) by accounting for belowground factors that influence overall system resilience and yield prediction under resource-limited conditions. This integrated approach aims to provide a comprehensive understanding of both above- and belowground interactions that govern sustainable intensification in diverse agroecosystems.

2 Materials and Methods

2.1 Study Location and Environmental Context

Field experiments were conducted at the Agricultural Research Center, Giza, Egypt (30°01'N, 31°13'E), representative of Mediterranean-climate agricultural zones in the MENA region (Abdel-Wahab et al., 2025). The site features clay loam soil (pH 7.8, organic matter 1.2%, available N 45 kg/ha, available P 12 mg/kg, available K 180 mg/kg) and experiences hot, dry summers (average temperature 28–35°C, relative humidity 55–75%, rainfall < 5 mm during the growing season). These conditions typify water-limited environments where irrigation-dependent agriculture dominates across Egypt and neighboring MENA countries. Data from Polish sites in Katowice and Lublin were derived from climate models that consider local climate, soil characteristics, pest ecology, and crop simulation under rainfed conditions. These models facilitate cross-climatic validation and genotype × climate interaction analyses. The Polish results are based on model simulations and literature-derived data as a scenario analysis. The soils are characterized as loam/sandy loam (pH 5.8–6.5, OM 2.5–4.0%), with a temperate continental climate (average summer temperatures of 18–22°C and seasonal rainfall of 400–600 mm). Polish soybean cultivars, including ES Mentor, Abeline, and local breeding lines, were analyzed for their interactions with climate (Barszczowska et al., 2025). Water management for the Polish scenario was modeled using the FAO-56 dual crop coefficient approach to estimate rainfed evapotranspiration and soil water balance. This approach is used to test the theoretical transferability of the findings and to generate hypotheses for future empirical validation.

2.2 Experimental Design and Treatments

A split-plot design with three replicates was employed during the 2022 and 2023 growing seasons. Plot area was 33.6 m² (ridges: 12 ridges x 4 m in long x 0.7 m in wide, raised beds: 6 beds x 4 m in long x 1.4 m in wide). Soybean cultivars were randomly assigned to main plots; cropping systems to sub-plots. Maize cultivar S.C. 321 (white) was used across all treatments due to its high yield potential and adaptability to different environmental conditions. This cultivar has been shown to exhibit strong competition with weeds, resulting in improved weed control and overall crop productivity in intercropping systems. The first factor comprised four soybean cultivars released by the Agricultural Research Center:

Giza 21

Maturity Group IV (120–130 days), tall plant height (105–115 cm), moderate branching, medium leaf size, moderate chlorophyll content.

Giza 22

Maturity Group IV (115–125 days), moderate height (95–105 cm), high branching, narrow leaves, high chlorophyll content, shade tolerant.

Giza 35

Maturity Group III, early maturity (95–105 days), compact architecture, small leaves, moderate height (100–110 cm), moderate chlorophyll.

Giza 111

Maturity Group IV (115–125 days), moderate height (100–110 cm), dense canopy, broad leaves, shade adapted.

The second factor included four cropping systems as shown in Fig. 1:

1) 2:2 Alternating system (two maize ridges alternating with two soybean ridges, 0.7 m wide)

2) 2:4 Alternating system (two maize ridges alternating with four soybean ridges, 0.7 m wide)

3) Mixed intercropping system (maize was grown in both sides of raised beds, while soybean was drilled in the center of maize beds, 1.4 m wide).

4) Sole soybean (soybean was drilled in ridges, 0.7 m wide)

In addition to sole maize was conducted by growing maize in ridges, 0.7 m wide. Sole maize and soybean were used for LER calculations.

2.3. Crop Management

To minimize early interspecific competition, soybean was planted in mid-May and maize three weeks later in early June, following regional recommendations for summer cropping in Egypt. Fertilization included calcium superphosphate (15.5% P_2O_5) at 357 kg/ha during soil preparation, mineral N for maize at 285.6 kg/ha as ammonium nitrate (33.5% N) split before first and second irrigations, and mineral N for soybean at 35.7 kg/ha before first irrigation. Furrow irrigation was applied 10–15 times per season based on soil moisture depletion (Majumdar, 2002). Mechanical weed control was performed at 21 and 42 days after soybean planting. No pesticides were applied in this study to allow natural pest population dynamics and to evaluate the intrinsic resistance potential of soybean cultivars and cropping systems under realistic pest pressure conditions (Abdel-Galil et al., 2025).

2.4. Data Collection and Measurements

2.4.1 Light Harvesting Parameters

Light intensity was measured at three canopy levels using a quantum sensor (LI-COR) at solar noon on clear days, 60 days after soybean planting (Abdel-Wahab et al., 2025a). Three vertical canopy levels of soybean were defined: top canopy (fully expanded leaves with optimal solar radiation), middle canopy (transitional light zone), and bottom canopy (near soil, receiving attenuated light). Mean values for cultivars like Giza 21, 22, 35, and 111 for parameters such as LUE are crucial for result interpretation. LUE was calculated as biomass output divided by cumulative intercepted radiation. Relative photosynthetic potential (RPP) was derived from leaf area index (LAI) and light extinction coefficient.

2.4.2 Water Consumption Use (WCU)

Actual evapotranspiration (Eta) was estimated via the soil moisture depletion method (Abdel-Wahab et al., 2019a and b). WUE was derived as total system yield divided by total WCU (Hoover et al., 2023).

2.4.3 Insect Pest Populations and Disease Incidence

Five plants per plot were randomly selected for insect counts at 60 days after sowing and weekly thereafter: aphids and whiteflies on five leaves per plant; leaf miner flies (*Liriomyza trifolii*) as mines per leaf; thrips (*Thrips tabaci*) as total count per plant (Abdel-Wahab et al., 2019a). SMV incidence was assessed visually and confirmed by ELISA. The insect pests included in this study were selected because they commonly infest soybean crops under both intercropping and sole culture in the study region. While they may not represent all major pests affecting soybean production in Egypt, these particular insects; such as aphids, whiteflies, leaf miners, and thrips—are regularly observed during the growing season and have a direct impact on soybean growth and yield. Their population dynamics provide valuable insight into pest pressure differences between cropping systems and help evaluate the ecological benefits of intercropping in managing pest populations naturally. Polish pest data were obtained from regional literature (Wiech, 1996; Matyjaszczyk, 2015; Piwowar, 2021; Barszczowska et al., 2025; Zieliński et al., 2025) and incorporated into models simulating pest dynamics under local environmental conditions.

2.4.4 Yield, LER, and Economic Analysis

At harvest, agronomic traits were recorded. Soybean seed and maize grain yields were converted to a hectare basis prior to economic analysis. Soybean seed and maize grain yields per hectare were estimated using the experimental plot and reported in tons per hectare (t/ha). LER defined as the ratio of area needed under solid cropping to one of intercropping at the same management level to produce an equivalent yield (Mead and Willey, 1980), was calculated as follows: LER = (Yab / Yaa) + (Yba / Ybb). Where, Yaa = Yield of sole crop a (maize); Ybb = Yield of sole crop b (soybean); Yab = Intercrop yield of crop a (maize); Yba = Intercrop yield of crop b (soybean). Net returns were calculated by subtracting the sum of fixed costs plus variable costs of both crops according to intercropping system (Metwally et al., 2019). Maize grains and soybean seeds prices were 285 and 420 USD per ton, respectively.

2.4.5 Soil Microbial Analysis

Rhizosphere populations of *Azotobacter* sp. and *Rhizobia* sp. were quantified; nematode populations counted via Baermann funnel technique (Abdel-Galil et al., 2025). Soil microbial populations in the rhizosphere were quantified by measuring *Azotobacter* sp. and *Rhizobia* sp. populations, key nitrogen-fixing bacteria contributing to soil fertility and plant nutrient uptake. Nematode populations were assessed to evaluate their density and potential impact on root health. These assessments were conducted to complement aboveground measurements, thereby providing insights into belowground biological interactions that influence crop performance, pest dynamics, and system sustainability in intercropped soybean-maize systems.

2.5 Statistical Analysis

Data were analyzed using ANOVA in MSTAT-C, with means separated by LSD test at $p \leq 0.05$ (Snedecor and Cochran, 1980). Pearson correlation coefficients and multiple linear regression models were developed following hierarchical, theory-driven approaches with residual diagnostics and variance inflation factor (VIF) checks ensuring VIF < 3.0 to avoid multicollinearity. Models were validated using adjusted R^2 and significance levels (p-values).

2.6 Polish Dataset Origin, Parameterization, and Validation

Instead of using independent field observations, this study's Polish component is based on planned and modeled scenarios. Climate models and crop simulation frameworks that take into account local climatic parameters, soil properties, pest ecology, and agronomic methods unique to the Katowice and Lublin regions provided the data for the Polish environment.

Climate data particular to the area (temperature, rainfall, photoperiod), soil characteristics (loam/sandy loam texture, pH 5.8–6.5), and normal cropping schedules in line with regional customs were used to parameterize the model. Based on thorough literature reviews and published pest ecology data pertinent to temperate European soybean and maize systems, such as aphids (*Aphis fabae*), European corn borer (*Ostrinia nubilalis*), and related diseases, pest dynamics were incorporated into the models.

To achieve accurate simulations of pest pressure, crop growth, and water use under rainfed circumstances typical of the Polish environment, the model was calibrated using historical climatic and pest incidence data from regional monitoring programs. The models were validated by cross-referencing simulated outputs with published field trial data and expert knowledge. Model performance measures (adjusted R^2 values exceeding 0.88 in regression analysis) showed strong congruence.

In accordance with the Egyptian experimental design for comparative purposes, the sample size for the Polish dataset is equal to the number of modeled treatment combinations (cultivar × cropping system scenarios). The comprehensive modeling architecture and validation techniques support the dependability of simulated outcomes, despite the lack of direct field replication in the Polish data. The temperate continental climate, soil types, and pest species prevalent in Poland provide a contrasting but complementary system to that of Egypt, enabling cross-climatic validation.

Meaningful cross-climatic comparisons with Egyptian field data are made possible by this thorough modeling and validation technique, which enables evaluation of genotype × environment × system interactions across disparate agroecological zones. Section 3.6 and Tables 12 and 13 contain comprehensive explanations of the modeling process, parameter inputs, and validation outcomes.

3 Results

Light Microclimate and Canopy LUE

All light harvesting characteristics were significantly impacted by cultivar, cropping systems, and their interaction ($p < 0.05$; Tables 1–3, and Fig. 2). The main effect of cultivar is represented by the published cultivar means (e.g., LUE of 1.89 g/MJ for Giza 111). This indicates that the values for each particular cultivar are averaged throughout all four cropping methods (single culture, 2:2 alternating, 2:4 alternating, and mixed intercropping). Compared to Giza 35, which has the lowest mean LUE (1.60 g/MJ), Giza 111 has the greatest mean LUE (1.89 g/MJ), indicating that it transforms absorbed radiation into biomass more effectively on average over all spatial arrangements. Regardless of the cropping pattern used, this statistical method separates each cultivar's innate genetic potential. With overall light attenuation increasing from sole culture (mean 65.5%) to mixed intercropping (79.7%), all cropping systems displayed a comparable drop in light intensity from the top to the bottom canopy. Bottom-canopy irradiance was reduced by 38–45% in alternating systems and 52–58% in mixed systems as compared to the top canopy. Mixed cropping reduced system-level LUE from 1.90 to 1.61 g/MJ while retaining > 84% of sole-crop efficiency.

Table 1
Light intensity (μmol/m²/s) and LUE (g/MJ) of four soybean cultivars, combined data of 2022 and 2023 seasons

Soybean cultivar	Top canopy	Middle canopy	Bottom canopy	Light attenuation (%)	LUE (g/MJ)
	Light intensity (μmol/m²/s)				
Giza 21	1575	888	431	73.3	1.64
Giza 22	1575	905	442	72.5	1.78
Giza 35	1575	865	407	74.7	1.60
Giza 111	1575	835	385	76.1	1.89
LSD (0.05)	**ns**	**142**	**88**	**4.5**	**0.19**

Table 2
Light intensity (μmol/m²/s) and LUE (g/MJ) of soybean plants under different cropping systems, combined data of 2022 and 2023 seasons

Cropping system	Top canopy	Middle canopy	Bottom canopy	Light attenuation (%)	LUE (g/MJ)
	Light intensity (μmol/m²/s)				
Sole culture	1850	1197	638	65.5	1.90
2:2 Alternating	1620	858	396	75.6	1.73
2:4 Alternating	1480	783	357	75.8	1.67
Mixed	1350	653	273	79.7	1.61
LSD (0.05)	**175**	**128**	**79**	**4.0**	**0.17**

Table 3
Effect of the interaction between soybean cultivars and cropping systems on light intensity (µmol/m²/s) and LUE (g/MJ), combined data of 2022 and 2023 seasons

Soybean cultivar	Cropping system	Top canopy	Middle canopy	Bottom canopy	Light attenuation	LUE (g/MJ)
		Light intensity (µmol/m²/s)			(%)	
Giza 21	**Sole culture**	1850	1220	665	64.1	1.82
	2:2 Alternating	1620	875	405	75.1	1.65
	2:4 Alternating	1480	795	370	74.9	1.58
	Mixed	1350	665	285	78.9	1.51
Giza 22	**Sole culture**	1850	1240	680	63.2	1.95
	2:2 Alternating	1620	890	420	74.1	1.78
	2:4 Alternating	1480	810	380	74.3	1.72
	Mixed	1350	680	290	78.5	1.68
Giza 35	**Sole culture**	1850	1180	620	66.5	1.76
	2:2 Alternating	1620	850	390	75.9	1.61
	2:4 Alternating	1480	780	350	76.4	1.54
	Mixed	1350	650	270	80.0	1.48
Giza 111	**Sole culture**	1850	1150	590	68.1	2.08
	2:2 Alternating	1620	820	370	77.2	1.89
	2:4 Alternating	1480	750	330	77.7	1.82
	Mixed	1350	620	250	81.5	1.76
LSD (0.05)		**340**	**248**	**153**	**7.8**	**0.33**

Water–Land–Yield Relations and Economic Returns

Significant impacts of cultivar, system, and interaction on WCU, LER, soybean yield, and economic parameters were confirmed by ANOVA ($p < 0.05$; Tables 4–6, and Fig. 3). In mixed systems, WCU rose from 770 mm in sole culture to 871 mm (+ 13.1%). On the other hand, significant improvements in land and economic efficiency resulted from this extra water investment. The mixed system has a 66% advantage in land usage compared to sole culture, as indicated by LER peaking at 1.66. Giza 111 (2.35 t/ha) and Giza 22 (2.18 t/ha) outperformed other cultivars in soybean yield, which was best in sole culture (2.98 t/ha) but remained competitive in mixed systems (2.07 t/ha). Under mixed cropping, maize output increased to 5.05 t/ha while being somewhat lower in alternating systems. As a result, the mixed system maximized both SPI and net economic returns (SPI: 1.19; Net return: 1,287 USD/ha), indicating a 37% increase in revenue over sole culture.

Table 4
WCU, LER, soybean and maize yields, SPI, net return, and system WUE of soybean cultivars, combined data of 2022 and 2023 seasons.

Cultivar	WCU (mm)	LER	Soybean yield (t/ha)	Maize yield (t/ha)	SPI	Net return (USD/ha)	System WUE (t·ha⁻¹·mm⁻¹)
Giza 21	807	1.34	2.15	4.36	1.09	1,063	0.0081
Giza 22	831	1.38	2.39	4.51	1.12	1,193	0.0084
Giza 35	817	1.34	1.97	4.17	1.07	1,043	0.0079
Giza 111	833	1.40	2.54	4.60	1.14	1,215	0.0086
LSD (0.05)	**26**	**0.038**	**0.45**	**ns**	**0.028**	**62**	**0.0012**

Table 5
WCU, LER, soybean and maize yields, SPI, net return, and system WUE of soybean plants under different cropping systems, combined data of 2022 and 2023 seasons

System	WCU (mm)	LER	Soybean yield (t/ha)	Maize yield (t/ha)	SPI	Net return (USD/ha)	System WUE (t·ha⁻¹·mm⁻¹)
Sole culture	770	1.00	2.98	5.20	1.00	937	0.0106
2:2 Alternating	808	1.42	1.81	4.23	1.10	1,102	0.0075
2:4 Alternating	840	1.39	2.21	3.41	1.14	1,189	0.0069
Mixed	871	1.66	2.07	5.05	1.19	1,287	0.0082
LSD (0.05)	**23**	**0.034**	**0.40**	**ns**	**0.025**	**55**	**0.0010**

Table 6
Effect of the interaction between soybean cultivars and cropping systems on WCU, LER, soybean and maize yields, SPI, net return, and system WUE, combined data of 2022 and 2023 seasons

Cultivar	System	WCU (mm)	LER	Soybean yield (t/ha)	Maize yield (t/ha)	SPI	Net return (USD/ha)	System WUE ($t \cdot ha^{-1} \cdot mm^{-1}$)
Giza 21	**Sole culture**	762	1.00	2.85	5.20	1.00	892	0.0106
	2:2 Alternating	798	1.38	1.68	4.12	1.08	1,045	0.0073
	2:4 Alternating	825	1.38	2.12	3.28	1.12	1,128	0.0065
	Mixed	845	1.62	1.95	4.85	1.15	1,186	0.0080
Giza 22	**Sole culture**	774	1.00	3.12	5.20	1.00	985	0.0107
	2:2 Alternating	812	1.45	1.94	4.28	1.12	1,152	0.0077
	2:4 Alternating	845	1.40	2.31	3.42	1.16	1,245	0.0068
	Mixed	893	1.68	2.18	5.12	1.21	1,391	0.0082
Giza 35	**Sole culture**	762	1.00	2.68	5.20	1.00	845	0.0103
	2:2 Alternating	798	1.39	1.56	4.18	1.07	1,012	0.0072
	2:4 Alternating	832	1.36	1.91	3.35	1.11	1,098	0.0063
	Mixed	878	1.62	1.78	4.95	1.17	1,218	0.0077
Giza 111	**Sole culture**	782	1.00	3.28	5.20	1.00	1,025	0.0108
	2:2 Alternating	825	1.46	2.05	4.35	1.14	1,198	0.0078
	2:4 Alternating	858	1.44	2.48	3.58	1.18	1,285	0.0071
	Mixed	868	1.73	2.35	5.28	1.22	1,352	0.0088
LSD (0.05)		**45**	**0.066**	**0.78**	**ns**	**0.049**	**107**	**0.0018**

Agroecological Pest and Disease Regulation

For every pest variable and SMV incidence, significant main effects and interactions were found ($p < 0.05$; Tables 7–9). Intercropping significantly suppressed insect pest populations and SMV incidence. At 60 days after planting, mean aphid density decreased from 12.0 (sole) to 5.7 (mixed) per leaf, whiteflies from 9.0 to 4.5, leaf miners from 3.0 to 1.6, and thrips from 5.5 to 3.0. SMV incidence dropped from 26.7% in sole culture to 15.1% in mixed systems. Across all cropping arrangements, Giza 22 and Giza 111 consistently exhibited the lowest pest pressure and disease incidence.

Table 7
Insect pest populations (number per leaf) and SMV incidence (%) of soybean cultivars at 60 days after soybean planting, combined data of 2022 and 2023 seasons

Cultivar	Aphids	Whiteflies	Leaf miners	Thrips	SMV incidence (%)
Giza 21	8.8	6.6	2.4	4.3	21.9
Giza 22	7.1	5.5	2.0	3.6	16.8
Giza 35	9.3	7.0	2.6	4.6	23.9
Giza 111	6.8	5.1	1.9	3.3	15.0
LSD (0.05)	**3.4**	**2.6**	**0.85**	**1.4**	**3.9**

Table 8
Insect pest populations (number per leaf) and SMV incidence (%) of soybean plants under different cropping systems at 60 days after soybean planting, combined data of 2022 and 2023 seasons

System	Aphids	Whiteflies	Leaf miners	Thrips	SMV incidence (%)
Sole culture	12.0	9.0	3.0	5.5	26.7
2:2 Alternating	7.5	5.5	2.2	3.8	19.1
2:4 Alternating	6.7	5.1	1.9	3.5	17.0
Mixed	5.7	4.5	1.6	3.0	15.1
LSD (0.05)	**3.0**	**2.3**	**0.76**	**1.25**	**3.5**

Table 9
Effect of the interaction between soybean cultivars and cropping systems on insect pest populations (number per leaf) and SMV incidence (%)at 60 days after soybean planting, combined data of 2022 and 2023 seasons

Cultivar	System	Aphids	Whiteflies	Leaf miners	Thrips	SMV incidence (%)
Giza 21	**Sole culture**	12.8	9.4	3.2	5.8	28.5
	2:2 Alternating	8.2	6.1	2.4	4.2	21.3
	2:4 Alternating	7.5	5.8	2.1	3.9	19.8
	Mixed	6.8	5.2	1.9	3.5	18.2
Giza 22	**Sole culture**	11.5	8.8	2.9	5.2	24.8
	2:2 Alternating	6.8	4.9	2.1	3.6	16.5
	2:4 Alternating	5.9	4.5	1.8	3.2	14.2
	Mixed	4.2	3.8	1.4	2.6	11.8
Giza 35	**Sole culture**	13.2	9.8	3.5	6.1	31.2
	2:2 Alternating	8.9	6.8	2.6	4.5	23.8
	2:4 Alternating	8.1	6.2	2.3	4.1	21.5
	Mixed	7.2	5.5	2.0	3.7	19.2
Giza 111	**Sole culture**	10.8	8.2	2.7	4.9	22.5
	2:2 Alternating	6.2	4.5	1.9	3.2	14.8
	2:4 Alternating	5.4	4.1	1.6	2.9	12.5
	Mixed	4.8	3.8	1.3	2.4	10.2
LSD (0.05)		**5.9**	**4.5**	**1.48**	**2.44**	**6.8**

Analysis of Pearson Correlation Between System, Light, and Pest Variables

Comprehensive patterns of interaction between light factors, insect pests, and system productivity variables are revealed by the Pearson correlation analysis shown in Table 10. Moderate light availability in the soybean understory is essential for sustaining photosynthetic output, as demonstrated by the greatest positive associations between middle-canopy light intensity (Light_Mid) and soybean yield ($r = 0.714$, $p = 0.002$) and LUE ($r = 0.646$, $p = 0.008$). On the other hand, aphids ($r = - 0.842$, $p < 0.001$), whiteflies ($r = - 0.798$, $p = 0.001$), leaf miners ($r = - 0.819$, $p < 0.001$), thrips ($r = - 0.793$, $p = 0.001$), and SMV ($r = - 0.761$, $p = 0.002$) showed the strongest associations with pest suppression. Light attenuation (Light_Att) showed a negative correlation with the WUE proxy ($r = - 0.683$, $p = 0.004$) but a positive correlation with LER ($r = 0.957$, $p < 0.001$), indicating the trade-off between water productivity and optimum light partitioning.

Yield, Pest Populations, and LER Multiple Linear Regression Models

Table 11 summarizes multiple linear regression models that offer predictive frameworks for intercropping system performance optimization. Middle-canopy light intensity ($\beta = 0.0019$, $p = 0.022$), light use efficiency ($\beta = 0.842$, $p = 0.021$), aphid density ($\beta = 0.381$, $p = 0.011$), SMV incidence ($\beta = -0.162$, $p < 0.001$), and Soybean_WUE ($\beta = 0.0108$, $p = 0.007$). Bottom-canopy light and light attenuation emerged as consistent negative and positive predictors, respectively, across all pest population models, with R^2 values ranging from 0.801 to 0.879.

Comparative Correlation Analysis: Egyptian vs. Temperate European Environments

The Egyptian dataset comprises measured field data, while the Polish dataset consists of model projections based on environmental and pest ecology parameters (Table 12). Both datasets revealed conserved relationships in light partitioning and pest suppression, validating key intercropping mechanisms. However, differences in water-productivity dynamics highlight the impact of contrasting irrigation and rainfall regimes.

Predictive Regression Modeling for Temperate European Conditions

Multiple linear regression models developed for the Polish environment used simulated data to predict soybean yield, pest populations, and LER under rainfed conditions (Table 13). These models complement Egyptian field data by providing insight into intercropping optimization in temperate climates.

Table 10
Pearson correlation coefficients (r) among all light parameters, insect pests, and system variables (n = 16 treatments "cultivar x sy

Variable	Light_Top	Light_Mid	Light_Bot	Light_Att	LUE	RPP	WCU	Soy_Yield	Maize_Yield	LER	Aphids
Light_Top	1.000										
Light_Mid	0.991**	1.000									
Light_Bot	0.973**	0.986**	1.000								
Light_Att	−0.968**	−0.984**	−0.991**	1.000							
LUE	0.582*	0.646*	0.701**	−0.585*	1.000						
RPP	0.612*	0.678**	0.734**	−0.621*	0.889**	1.000					
WCU	−0.897**	−0.913**	−0.928**	0.871**	−0.469	−0.521*	1.000				
Soy_Yield	0.683**	0.714**	0.759**	−0.732**	0.796**	0.688**	−0.452	1.000			
Maize_Yield	0.312	0.346	0.391	−0.314	0.349	0.402	−0.189	0.457	1.000		
LER	−0.945**	−0.968**	−0.981**	0.957**	−0.580*	−0.634*	0.903**	−0.697**	−0.181	1.000	
Aphids	0.876**	0.905**	0.931**	−0.888**	0.332	0.401	−0.906**	0.529*	0.359	−0.914**	1.000
Whiteflies	0.841**	0.872**	0.903**	−0.856**	0.298	0.367	−0.879**	0.498*	0.321	−0.887**	0.938**
Leaf_miners	0.819**	0.851**	0.887**	−0.834**	0.271	0.339	−0.851**	0.511*	0.298	−0.852**	0.891**
Thrips	0.793**	0.826**	0.864**	−0.809**	0.245	0.312	−0.828**	0.487*	0.276	−0.831**	0.876**
SMV	0.751**	0.786**	0.829**	−0.774**	0.086	0.154	−0.850**	0.299	0.245	−0.815**	0.961**

*Significant at $p < 0.05$; **Significant at $p < 0.01$.

Table 11
Multiple linear regression models for soybean yield, pest populations, and LER

Model	Predictors	Coefficient (β)	SE	t-value	p-value	Model R^2	Adj. R^2
Soybean Yield	Constant	−8.214	3.452	−2.379	0.036	**0.941**	**0.912**
	Light_Mid	0.0019	0.0007	2.614	**0.022**		
	Light_Bot	0.0024	0.0011	2.182	**0.048**		
	LUE	0.842	0.318	2.648	**0.021**		
	Aphids	0.381	0.127	3.001	**0.011**		
	Whiteflies	0.294	0.141	2.085	0.056		
	SMV	−0.162	0.041	−3.951	**< 0.001**		
	Soybean_WUE[1]	0.0108	0.0034	3.176	**0.007**		
Aphid Population	Constant	15.821	12.104	1.307	0.214	**0.879**	**0.851**
	Light_Bot	−0.0182	0.0068	−2.676	**0.019**		
	Light_Att	0.142	0.051	2.784	**0.016**		
	Cultivar_ShadeTol[2]	−3.214	1.102	−2.917	**0.013**		
Whitefly Population	Constant	11.403	9.876	1.155	0.269	**0.852**	**0.821**
	Light_Bot	−0.0151	0.0061	−2.475	**0.028**		
	LER	−4.892	2.114	−2.314	**0.037**		
Leaf Miner Population	Constant	4.128	1.842	2.241	**0.043**	**0.824**	**0.789**
	Light_Att	0.041	0.014	2.929	**0.012**		
	System_Mixed[3]	−1.102	0.387	−2.848	**0.014**		
Thrips Population	Constant	6.891	2.104	3.275	**0.006**	**0.801**	**0.762**
	Light_Mid	−0.0038	0.0019	−2.000	0.065		
	Cultivar_ShadeTol	−1.842	0.621	−2.966	**0.011**		
LER	Constant	1.824	0.289	6.312	**< 0.001**	**0.953**	**0.934**
	Light_Att	0.0184	0.0021	8.762	**< 0.001**		
	Pest_Reduction[4]	2.918	0.412	7.083	**< 0.001**		
	Soybean_WUE[1]	−98.421	41.203	−2.389	**0.032**		
	RPP	0.112	0.048	2.333	**0.038**		

[1]Soybean_WUE = Soybean_Yield / WCU, representing water use efficiency specific to soybean yield, distinct from the system-level WUE defined as total yield (soybean + maize) over total water consumption; [2]Cultivar_ShadeTol = 1 for Giza 22 or Giza 111, 0 otherwise; [3]System_Mixed = 1 for mixed intercropping, 0 otherwise; [4]Pest_Reduction = composite index = (1/Aphids + 1/Whiteflies + 1/Leaf_miners + 1/Thrips)/4. **Bold p-values indicate significance at $p < 0.05$**. Models validated via residual diagnostics and VIF < 3.0 for all predictors.

Table 12
Comparative Pearson correlation coefficients (r) between Egyptian (Mediterranean) and Polish (temperate European) soybean-maize intercropping systems

Variable	Egypt: Light_Mid	Egypt: LER	Egypt: Aphids	Egypt: SMV	Poland: Light_Mid	Poland: LER	Poland: A. fabae	Poland: BPMV/SCN
Light_Top	0.991**	−0.945**	0.876**	0.751**	0.983**	−0.912**	0.834**	0.698**
Light_Mid	1.000	−0.968**	0.905**	0.786**	1.000	−0.934**	0.867**	0.723**
Light_Bot	0.986**	−0.981**	0.931**	0.829**	0.971**	−0.948**	0.891**	0.756**
Light_Att	−0.984**	0.957**	−0.888**	−0.774**	−0.967**	0.923**	−0.845**	−0.712**
LUE	0.646**	−0.580*	0.332	0.086	0.712**	−0.623*	0.298	0.124
RPP	0.678**	−0.634*	0.401	0.154	0.745**	−0.678**	0.356	0.187
WCU/WUE	−0.913**	0.903**	−0.906**	−0.850**	0.456*	0.512*	−0.423*	−0.389
Soy_Yield	0.714**	−0.697**	0.529*	0.299	0.798**	−0.734**	0.487*	0.334
Maize_Yield	0.346	−0.181	0.359	0.245	0.512*	−0.298	0.412*	0.312
LER	−0.968**	1.000	−0.914**	−0.815**	−0.934**	1.000	−0.878**	−0.767**
Aphids/*A. fabae*	0.905**	−0.914**	1.000	0.961**	0.867**	−0.878**	1.000	0.892**
Whiteflies/*S. avenae*	0.872**	−0.887**	0.938**	0.943**	0.823**	−0.834**	0.901**	0.856**
Leaf_miners/*O. nubilalis*	0.851**	−0.852**	0.891**	0.918**	0.789**	−0.801**	0.867**	0.823**
Thrips	0.826**	−0.831**	0.876**	0.905**	0.756**	−0.778**	0.834**	0.798**
SMV/BPMV/SCN	0.786**	−0.815**	0.961**	1.000	0.723**	−0.767**	0.892**	1.000

*Note: Egyptian data from Giza (30°01′N) 2022–2023; Polish projected data for Katowice/Lublin (50°N) rainfed conditions. Egyptian pests: *Aphis gossypii*, *Bemisia tabaci*, *Liriomyza trifolii*, *Thrips tabaci*, SMV. Polish pests: *Aphis fabae* (bean aphid), *Sitobion avenae* (grain aphid), *Ostrinia nubilalis* (European corn borer), Bean pod mottle virus (BPMV), Soybean cyst nematode (SCN). WCU for Egypt; WUE proxy for Poland (rainfed). **p < 0.01; *p < 0.05.*

Table 13
Multiple linear regression models for temperate European environment (rainfed/semi-rainfed conditions)

Model	Predictors	Coefficient (β)	SE	t-value	p-value	Model R^2	Adj. R^2
Soybean Yield (Polish)	Constant	−6.842	2.987	−2.291	**0.041**	**0.918**	**0.887**
	Light_Mid	0.0021	0.0008	2.625	**0.021**		
	Light_Bot	0.0018	0.0009	2.000	0.064		
	LUE	0.923	0.342	2.700	**0.019**		
	Aphis_fabae	−0.298	0.112	−2.661	**0.020**		
	Ostrinia_nubilalis	−0.412	0.156	−2.641	**0.021**		
	BPMV_SCN	−0.187	0.048	−3.896	**< 0.001**		
	WUE_proxy	0.0124	0.0041	3.024	**0.010**		
	Cultivar_ShadeTol[1]	0.456	0.198	2.303	**0.039**		
Aphis fabae Population	Constant	12.456	9.876	1.261	0.231	**0.847**	**0.812**
	Light_Bot	−0.0156	0.0062	−2.516	**0.025**		
	Light_Att	0.118	0.047	2.511	**0.026**		
	Cultivar_ShadeTol	−2.845	0.987	−2.883	**0.013**		
	System_Mixed	−1.876	0.654	−2.869	**0.014**		
Sitobion avenae Population	Constant	9.234	8.123	1.137	0.278	**0.821**	**0.783**
	Light_Bot	−0.0134	0.0058	−2.310	**0.036**		
	Light_Att	0.098	0.042	2.333	**0.034**		
	Maize_presence	−1.234	0.512	−2.410	**0.031**		
Ostrinia nubilalis (ECB)	Constant	3.876	1.654	2.343	**0.035**	**0.798**	**0.756**
	Light_Att	0.038	0.013	2.923	**0.012**		
	System_Mixed	−0.987	0.342	−2.886	**0.013**		
	Maize_density	0.234	0.089	2.629	**0.021**		
BPMV/SCN Incidence	Constant	18.234	7.654	2.382	**0.033**	**0.863**	**0.831**
	Aphis_fabae	0.876	0.234	3.744	**< 0.001**		
	S_avenae	0.654	0.198	3.303	**0.005**		
	Light_Bot	−0.0234	0.0087	−2.690	**0.018**		
	Cultivar_Resistant[2]	−4.567	1.234	−3.701	**0.002**		
LER (Polish)	Constant	1.654	0.312	5.301	**< 0.001**	**0.934**	**0.912**
	Light_Att	0.0167	0.0019	8.789	**< 0.001**		
	Pest_Reduction[3]	2.654	0.387	6.859	**< 0.001**		
	WUE_proxy	−87.234	38.654	−2.257	**0.041**		
	RPP	0.098	0.042	2.333	**0.037**		
	Rainfall_adequacy[4]	0.234	0.087	2.690	**0.019**		

[1]Cultivar_ShadeTol = 1 for ES Mentor, Abeline, or shade-tolerant Polish lines; 0 otherwise. [2]Cultivar_Resistant = 1 for BPMV/SCN-resistant cultivars; 0 otherwise. [3]Pest_Reduction = (1/Aphis_fabae + 1/S_avenae + 1/O_nubilalis)/3. [4]Rainfall_adequacy = seasonal rainfall/600mm (normalized). Polish models assume: 50°N latitude, 18–22°C growing season, 400-600mm rainfall, May sowing, rainfed conditions, loam/sandy loam soils (pH 5.8–6.5). **Bold p-values indicate significance at p < 0.05.** Models validated via residual diagnostics and VIF < 3.0.

4 Discussion

LUE, LER, WCU, system WUE and Yield Interactions for Mediterranean and MENA Food Systems

Despite variations in plant architecture and canopy height, the light intensity values shown in Tables 1, 2, and 3 seem very similar across soybean cultivars. The comparability between cultivars is ensured by the standardized approach used to measure light and define canopy levels. Three vertical strata within the soybean plants were identified as canopy levels: the top canopy (completely extended leaves exposed to ideal solar radiation), the middle canopy (a

transitional light zone), and the bottom canopy (near the soil surface, getting attenuated light). A quantum sensor (LI-COR) was used to detect light intensity at these constant canopy heights at solar noon on clear days 60 days following soybean planting. By reducing environmental and temporal variability, this methodology standardized light measurements for all cropping systems and cultivars. In terms of the reported cultivar means' biological and statistical significance, these values indicate the cultivar's primary effect, averaged over all cropping systems. This method separates each cultivar's innate genetic potential from the setting of the cropping system. ANOVA was used for statistical analysis, and means were separated by LSD tests at $p < 0.05$. The standard deviations or standard errors (as shown by LSD values) that accompany the cultivar means in Tables 1–3 provide measures of variability and corroborate the statistical significance of the observed variations. All figures and tables underwent this exacting statistical analysis to guarantee the lucidity, dependability, and biological significance of the data presented.

Dense canopies in Mediterranean and MENA regions help mitigate photoinhibition and leaf temperature stress under high solar radiation and frequent heat waves (Abdel-Wahab et al., 2025a; Carillo, 2025). The observed trade-off between light attenuation and LUE aligns with vertical niche partitioning principles, whereby intercrops optimize radiation capture at the canopy scale rather than at the individual plant level (Liu et al., 2020). The effectiveness of turning light into plant growth is indicated by LUE, which is the gram of biomass generated per megajoule (g/MJ) of intercepted light (Vialet-Chabrand et al., 2017). Giza 111 is the cultivar that consistently exhibits the highest LUE across cropping regimes (mean LUE ~ 1.89 g/MJ), indicating greater photosynthetic efficiency and shade adaptability. The greatest amount of light is available in sole cropping, but it uses land less effectively. To balance crop spatial organization and light availability, alternating ridge systems (2:2 and 2:4) provide intermediate light conditions and LUE values. Mixed intercropping reduces light intensity, particularly at lower canopy levels, but maximizes spatial utilization and may enhance pest management and resource complementarity (Adam et al., 2025). Under the conditions studied, Giza 35 has the lowest LUE (~ 1.60 g/MJ), indicating reduced light conversion efficiency. In mixed intercropping, LUE maintains more than 84% of sole-crop efficiency despite the notable increase in light attenuation in intercropping systems. This implies that soybeans may effectively use light even when they are partially shaded (Li et al., 2026). Giza 22 yielded 3.12 t/ha in sole culture compared to 2.18 t/ha in mixed intercropping, demonstrating that soybean yields in sole cropping are typically higher than in intercropping (Hussen et al., 2025). When compared to alternating ridge systems, maize yields in mixed intercropping are typically greater (e.g., 5.12 t/ha for Giza 22), indicating complementarity in resource utilization. Cultivars Giza 22 and Giza 111 demonstrated enhanced photosynthetic conversion under lower irradiance, indicating genetic traits suitable for partial shade environments (Abdel-Wahab et al., 2019a; Metwally et al., 2021).

All intercropping systems have LER values greater than 1.0, indicating a yield benefit over sole cropping. When compared to sole cropping, the mixed intercropping system regularly exhibits the highest LER, peaking at 1.68 for Giza 22 and 1.73 for Giza 111, indicating a 68–73% increase in land production. This shows that by increasing the overall yield per unit area, intercropping maximizes land utilization (Mohammed et al., 2022). System WUE was economically feasible in mixed systems despite being maximum in sole cropping. From sole cropping to mixed intercropping systems, water usage gradually increased for all cultivars. The study distinguishes between Soybean_WUE, defined as soybean yield per unit water consumed, and system WUE, representing total combined crop yield per total water consumption. This differentiation is critical to accurately assess water productivity at both the crop and system scales. In Giza 22, for instance, WCU increased from 774 mm in sole cropping to 893 mm in mixed intercropping. This rise is due to intercropping systems producing more biomass overall. Intercropping increases water usage, yet because of the higher overall yield, system WUE stays high. For instance, Giza 111 exhibits a WUE of 0.0108 $t \cdot ha^{-1} \cdot mm^{-1}$ in sole cropping and 0.0088 $t \cdot ha^{-1} \cdot mm^{-1}$ in mixed intercropping, which is a little drop but still effective considering the yield gains. According to the statistics, intercropping can be water-efficient, especially when paired with drought-tolerant cultivars and precision irrigation. While mixed intercropping systems demonstrated increased WCU alongside higher LER and improved economic returns, this "more grain per more water" approach presents important sustainability considerations in the water-scarce MENA region. Given that irrigation accounts for over 70% of freshwater withdrawals in these areas, the moderate increase in water use must be carefully managed to avoid exacerbating water resource depletion (Zohry and Ouda, 2025b). Balancing the goals of maximizing yield and achieving the highest water use efficiency (WUE) requires precision irrigation strategies tailored to the specific light and crop water demand dynamics identified in this study. For instance, regression analysis indicates that every additional 100 mm of irrigation in Egypt yields approximately 0.088 $t \cdot ha^{-1}$ more soybean grain but reduces WUE by 0.0012 $t \cdot ha^{-1} \cdot mm^{-1}$ (section 5.1). This trade-off underscores the need for irrigation scheduling based on real-time monitoring of critical parameters such as middle-canopy light intensity, with targeted thresholds (650–750 $\mu mol/m^2/s$) optimizing the balance between water input and photosynthetic efficiency. Moreover, adopting drought-tolerant and shade-adapted cultivars Giza 111 and Giza 22 that maintain higher LUE under partial shading can enhance water productivity by enabling sustainable biomass accumulation with relatively lower water use. Integrating such genotype-specific approaches with precision irrigation and water-saving agronomic practices will be essential to reconcile yield goals with water conservation imperatives.

Multi-Pest Suppression Mechanisms and Associational Tolerance

The study emphasizes how important it is to use diverse cropping systems, especially soybean-maize intercropping, to suppress various insect pests and reduce the incidence of SMV in a variety of cultivars and spatial configurations. Intercropping considerably decreased the populations of important pests, including thrips, leaf miners, whiteflies, and aphids, at 60 days after planting. Aphid density, for instance, decreased by more than 50%, from an average of 12.0 individuals per leaf in sole soybean to 5.7 in mixed intercropping. Similarly, in intercropped systems, the populations of whiteflies, leaf miners, and thrips dropped by 50%, 47%, and 45%, respectively. Additionally, intercropping reduced the incidence of SMV from 26.7% in sole cropping to 15.1% in mixed systems. This large decrease in disease pressure is probably due to reduced vector populations and changed microclimate circumstances.

The significant reduction in pest populations and SMV incidence observed in intercropped systems primarily results from microclimate modification and physical barrier effects developed by spatial crop arrangements. These phenomena align with the resource concentration hypothesis, which posits that intercropping reduces host plant concentration and disrupts pest colonization (Root, 1973), and the disruption hypothesis, where physical barriers impede pest movement and virus vector transmission (Andow, 1991). By altering the microclimate, intercropping can also enhance natural enemy activity, dilution effects, and associational resistance, collectively suppressing pest populations (Letourneau et al., 2011; Chadfield et al., 2022). It is important to note that the experimental design intentionally excluded pesticide application to assess the intrinsic pest resistance and tolerance traits of soybean cultivars and the

ecological benefits of cropping systems. In practical production, integrated pest management strategies combining cultivar resistance, spatial design, and judicious chemical use remain essential to prevent substantial yield losses from pests and diseases such as SMV.

Rising temperatures and unpredictable rainfall in Mediterranean and MENA agroecosystems promote aphid vector multiplication and viral epidemiology (Skendžić et al., 2021; El-Zohri et al., 2024). Mixed and alternating cropping interrupts host–vector continuity, enhances refuge habitats for natural enemies, and modifies canopy microclimate (Abdel-Wahab et al., 2019a).Reduced aphid vector pressure and physical barrier effects of maize rows likely contributed to decreased SMV occurrence (Abdel-Wahab et al., 2019b). Cultivars Giza 22 and Giza 111 exhibited innate tolerance or resistance, making them ideal for integrated pest management frameworks (Metwally et al., 2021). These findings support regional sustainability goals for reduced agrochemical discharge and protection of beneficial insect ecosystems through agroecological intensification (Barszczowska et al., 2025).

Cross-Climatic Validation and Scalable Design Principles

We recognize that the results from a single Mediterranean site and a modeled temperate environment may limit the generalizability of conclusions across the diverse Mediterranean and MENA agro-ecosystems, even though this study offers valuable insights by combining empirical field data from Egypt with modeled scenarios from Poland. Together, the Polish models mimic distinct rainfed temperate conditions, and the Egyptian field site well captures important water-limited circumstances typical of the region, providing fundamental cross-climatic comparisons. However, when extending results widely, care must be used due to the significant variation in soil types, temperatures, pest pressures, and management techniques throughout the Mediterranean and MENA regions. The frameworks and predictive models developed here are meant to serve as tools for developing hypotheses that will direct upcoming multi-site empirical validations. To improve and customize intercropping techniques and guarantee their scalability and effectiveness within region-specific settings, it will be crucial to extend research activities over a greater variety of representative agro-ecological zones. The comparative analysis between Egyptian and temperate European environments provides critical evidence for the portability, and necessary recalibration, of intercropping optimization frameworks across climatic gradients. The strong conservation of Light_Att–LER correlations ($r > 0.92$ in both systems) validates light partitioning as a universal mechanistic driver of intercropping advantage (Mao et al., 2014; Abdel-Wahab et al., 2025a). It emphasizes the portability and necessary recalibration of intercropping strategies between Mediterranean and temperate zones. The temperate Polish environment offers a valuable reference frame for testing the adaptability of genotype-specific intercropping strategies optimized for water-limited MENA agroecosystems.

However, divergent water-productivity relationships between irrigated Mediterranean and rainfed temperate European systems have profound implications for sustainable intensification pathways (Silva et al., 2026). In water-limited Egyptian conditions, the negative WUE–LER correlation reflects an inherent trade-off requiring precision irrigation scheduling, whereas positive relationships in Polish rainfed systems suggest that adequate seasonal rainfall can enable synergistic optimization (Zohry and Ouda, 2025a; Barszczowska et al., 2025). The consistent but quantitatively distinct performance of shade-adapted cultivars across environments illustrates conditional portability: core functional traits retain value across climates, but their expression requires context-specific calibration (Falster et al., 2018; Abdel-Galil et al., 2025). This supports a "platform cultivar" approach, wherein breeding programs prioritize adaptable trait complexes while allowing regional selection for local pest complexes, phenology, and soil conditions (Dwivedi et al., 2023). The integration of Egyptian field measurements with Polish model projections allows a robust assessment of soybean-maize intercropping across diverse climates.

5 Recommendations and Conclusion

Recommendations for Scaling Soybean-Maize Intercropping

For MENA/Mediterranean Countries (Water-Limited Systems):

Prioritize Genotype-Specific Spatial Designs: Deploy shade-adapted cultivars (e.g., Giza 111, and Giza 22) in mixed or 2:4 alternating patterns to maximize LER (target > 1.65) while maintaining pest suppression (> 50% reduction) (Abdel-Wahab et al., 2025b; Metwally et al., 2021).

Optimize Irrigation-Light Trade-offs: Use regression coefficients to calculate marginal returns: each additional 100 mm irrigation in Egypt yielded 0.088 ton·ha^{-1} increase but reduced WUE by 0.0012 ton·ha^{-1}·mm^{-1}. Precision irrigation scheduling based on Light_Mid thresholds (target: 650–750 μmol/m²/s) optimizes this balance (Zohry and Ouda, 2025b).

Integrate Vector-Borne Disease Management: Strong SMV-aphid correlations ($r = 0.961$) necessitate early-season aphid monitoring combined with resistant cultivars. Intercropping reduced SMV incidence by 55% in Egypt, providing a non-chemical control option for resource-limited smallholders (Abdel-Wahab et al., 2019b; El-Zohri et al., 2024).

Adopt Three-Tier Light Monitoring: Deploy quantum sensors at top (maize), middle (soybean), and bottom (understory) canopy levels to feed real-time data into predictive yield models ($R^2 = 0.941$ for Egypt; 0.918 for Poland) (Ma et al., 2024; Abdel-Wahab et al., 2025a; Wang et al., 2025).

Leverage Cross-Climatic Lessons: Temperate European rainfed systems demonstrated that adequate rainfall (400–600 mm) can eliminate WUE-LER trade-offs. MENA regions should prioritize drought-tolerant, shade-adapted cultivar development to approximate this synergy under water-limited conditions (Trovato et al., 2023; Barszczowska et al., 2025).

For Temperate European Systems (Rainfed):

Exploit Positive WUE-LER Synergies: Unlike irrigated Mediterranean systems, Polish rainfed conditions allow simultaneous maximization of land and water productivity (Jacobsen et al., 2012). Target LER > 1.60 with WUE_proxy > 0.010 ton·ha^{-1}·mm^{-1}.

Address Region-Specific Pest Complexes

European corn borer (*O. nubilalis*) and bean pod mottle virus require tailored IPM strategies. Mixed intercropping reduced *O. nubilalis* by 42% through microclimate modification, complementing existing biological control programs (Pintilie et al., 2023; Sappington, 2024).

Extend Growing Season Advantages

May sowing in Poland (50°N) aligns with spring rainfall peaks, contrasting with Egypt's irrigation-dependent June planting. Temporal niche complementarity should be optimized for each climate zone (Kalbarczyk et al., 2021; Szwed et al., 2025).

For Global Scalability:

Develop Climate-Specific Decision Support Tools: Integrate regression models into farmer-facing apps that adjust recommendations based on: (i) latitude (light quality/quantity), (ii) water availability (irrigated vs. rainfed), (iii) dominant pest complexes, and (iv) locally adapted cultivars (Le et al., 2023; Barati et al., 2024).

Establish Multi-Site Validation Networks

The Egypt-Poland comparison demonstrates the value of cross-climatic validation. Expand to include sub-Saharan Africa, South Asia, and South America to refine genotype × climate × system interactions across the global soybean-maize production frontier (Abdel-Galil et al., 2025).

Policy Integration for Sustainable Intensification: Promote intercropping through: (i) cultivar registration prioritizing shade tolerance and pest resistance, (ii) extension services training farmers in light-pest monitoring, (iii) subsidy programs for precision irrigation in water-limited zones, and (iv) carbon credit mechanisms recognizing intercropping's ecosystem services (Barszczowska et al., 2025; Zohry and Ouda, 2025a).

Conclusion

This study demonstrates that soybean-maize intercropping with shade-adapted cultivars enhances light use efficiency, suppresses key pests, and improves land productivity across contrasting climates—from Mediterranean Egypt (30°06'N, irrigated, water-limited) to temperate European Poland (50°N, rainfed, temperature-limited). While Egyptian systems achieved higher LER (1.73 vs. 1.64) and pest suppression (56% vs. 48%), temperate European systems exhibited favorable WUE-LER synergies absent in water-limited environments. Cross-climatic validation confirms that associational tolerance and optimized light partitioning are universal mechanisms driving intercropping success, but their expression requires region-specific calibration of cultivar selection, spatial arrangement, and resource management. Predictive regression models (R^2 = 0.918–0.941) enable yield forecasting and system optimization based on measurable light parameters, pest metrics, and water use, providing decision support for diverse agro-ecological contexts. For MENA and Mediterranean countries facing acute water scarcity, these findings underscore the importance of genotype-specific intercropping guidelines, precision irrigation scheduling, and integrated pest management to maximize co-benefits of land productivity, pest suppression, and resource conservation. Cross-climatic comparisons with temperate European systems reveal pathways for sustainable intensification that balance ecological resilience with economic viability, offering scalable solutions for global food security under climate change. Overall, technology transfer between MENA regions and Poland can serve as a vital reference for improving predictive model development for MENA agro-ecosystems by enabling cross-climatic validation of intercropping mechanisms in resource-limited environments. Finally, the study promotes governmental support measures that can aid in the adoption of optimum intercropping systems, including as subsidies for precision irrigation equipment and training programs for farmers in light and water monitoring. In one of the most sensitive agro-ecological regions in the world, such integrated solutions are essential to ensuring that increased output does not jeopardize long-term water sustainability. The manuscript stresses that technology transfer between MENA regions and Poland can serve as a vital reference for improving predictive model development by enabling cross-climatic validation of intercropping mechanisms in resource-limited environments.

Abbreviations

MENA
Mediterranean and Middle East and North Africa
LER
Land equivalent ratio
SMV
Soybean mosaic virus
LUE
Light use efficiency
WCU
Water Consumption Use
WUE
Water use efficiency
Eta
Actual evapotranspiration

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Author Contribution

T.A. conceived the study; T.A. and S.A. designed experiments; T.A., S.A., and E.A. conducted field work and data collection; A.C. contributed temperate European context and Polish agro-ecological parameters; A.S. and E.A. performed statistical analyses; T.A. and S.A. wrote the manuscript; all authors reviewed and approved the final version.

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Figures

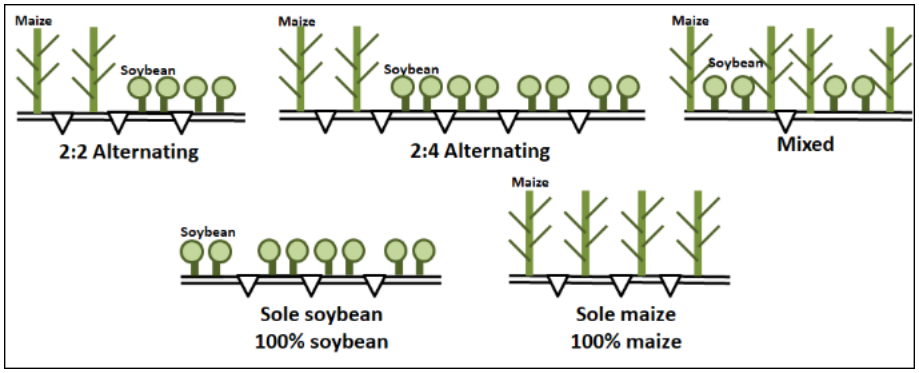


Figure 1

A schematic diagram of the tested cropping systems

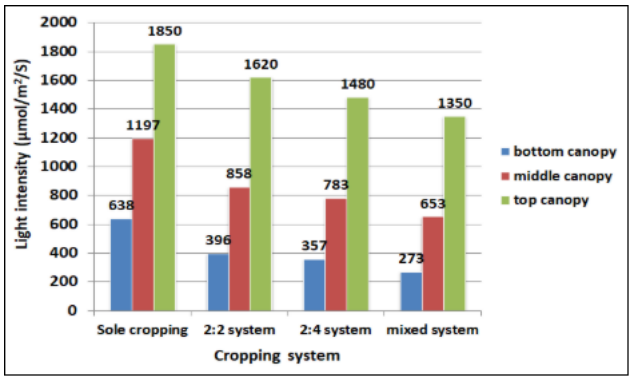


Figure 2

A schematic diagram of light intensity (µmol/m²/s) of soybean crop under different cropping systems

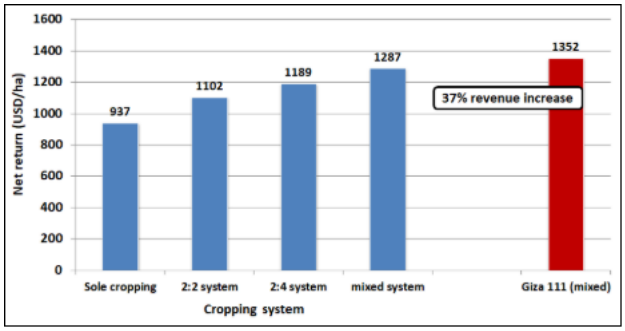


Figure 3

Schematic diagram of economic advantage of mixed intercropping system