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EVALUATION OF SUNFLOWER-SOYBEAN INTERCROPPING PATTERNS FOR GRAIN YIELD AND PLANT HEIGHT

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Abstract

Intercropping is an effective strategy for improving land-use efficiency and total system productivity by enabling complementary resource use among component crops. A field experiment was conducted during the 2022 growing season at the Research Area of the University of Agriculture Faisalabad, Sub-campus Depalpur, District Okara, Pakistan, to evaluate the effect of different sunflower–soybean intercropping patterns on the growth and yield of both crops. The experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications. It comprised eight treatments, including sole sunflower, sole soybean, and six sunflower–soybean row arrangements (1:1, 1:2, and 1:3) established under both simultaneous and 30-day relay sowing of soybean. Results showed that the cropping pattern had a highly significant effect on grain yield and plant height of both crops. The 1:1 simultaneous sowing pattern (T3) produced the highest achene yield of sunflower (1669.33 kg ha^{-1}) and the highest seed yield of soybean (1351.67 kg ha^{-1}), surpassing their respective sole cropping treatments. Sunflower plant height was greatest under sole cropping (T1, 136.71 cm) and was statistically comparable to T3 (134.04 cm), while soybean plant height was greatest under T3 (87.98 cm). Wider row ratios (1:2, 1:3) and relay sowing generally reduced yield and plant height in both crops, most notably under the 1:1

relay-sown pattern (T6), which produced the lowest soybean plant height. These findings indicate that the 1:1 row ratio under simultaneous sowing offers the most favorable balance of complementary resource use between sunflower and soybean and represents the optimum intercropping pattern for maximizing productivity of both crops under the agro-climatic conditions of Depalpur, Punjab, Pakistan.

Introduction:

Rapid population growth, shrinking arable land, and climate variability are major challenges for modern agriculture; these challenges not only deplete the natural resources available for cultivation but also require agricultural systems to produce more food to ensure food security (Afzal et al., 2025; Okolie et al., 2023). One optimum solution to these problems is adopting sustainable cropping systems; these systems not only enhance agricultural productivity but also conserve soil water and nutrients (Quintarelli et al.,2022). Intercropping is one of these systems, which can be defined as the practice of simultaneous cultivation of two or more crops during the same growing season on the same field. Intercropping has proven helpful not only in increasing resource-use efficiency, but also in enhancing overall agricultural productivity and promoting environmental sustainability (Gardarin et al., 2022). In contrast to monocropping, the cultivation of a single crop at one time takes an equal amount of natural resources, with lower yield. Intercropping also reduces pest incidence, weed pressure, soil erosion, and chances of crop failure (Kaur et al., 2024).

Intercropping is further categorized into four main types: row intercropping, mixed intercropping, relay intercropping, and strip intercropping. In row intercropping, cultivated plants are placed in distinct alternating rows, whereas in mixed intercropping, crops are grown without a defined row arrangement. In relay intercropping, the second crop is sown before the first crop reaches physiological maturity. In contrast, in strip intercropping, crops are cultivated in wide stripes that allow independent crop management while maintaining biological interactions. Row intercropping is the most widely used because it permits mechanized operations, maximizes resource use, partitions resources between component crops, and improves crop management. It minimizes interspecific competition while maximizing complementarity by providing an optimal spatial arrangement, which improves overall system productivity (Te et al., 2023).

Intercropping systems' success largely depends on choosing fitting crops with distinct physiological and morphological traits (Cheriere et al., 2023). One of the popular successful combinations is combining cereal, oilseed, and legume crops, this combination has shown positive results due to their contrasts in root depth, nutrient uptake, canopy structure, and growth duration. This system is further improved by leguminous crops, as they fix atmospheric nitrogen, which reduces the need for synthetic fertilizer by improving soil fertility. That is why this oilseed–legume intercropping has become a fairly positive sustainable system to boost agricultural yields while enhancing soil health (Raza et al., 2023).

One of the world's most important leguminous crops is soybean (*Glycine max* L.). This is because it is rich in nutrition and also has huge economic value, with 35-42% protein and 18-22% oil in its seed; it becomes a major source of oil and vegetable protein for both livestock feed and human consumption (Guo et al., 2022). Soybean, being important economically, also has many other benefits; one among those is that it makes symbiotic relationship with *Bradyrhizobium* species, which allows it to fix environmental nitrogen naturally, improving soil nitrogen reserves and fertility to support subsequent crops. It can also provide large organic residues that enhance soil microbial activity, structure, and long-term sustainability to support further cultivation (Pandit et al., 2026).

The best combination to be intercropped with soybean is sunflower (*Helianthus annuus* L.), which is a major oilseed crop cultivated around the globe due to its high-quality edible oil, relatively short growth cycle, and extraordinary adaptability. Sunflower oil contains high amounts of natural antioxidants and unsaturated fatty acids, which makes it best for human consumption, providing major nutrients (Petrenko et al., 2023). Pakistan has a major issue with huge oil import costs, which is one of the biggest burdens for the economy; sunflower can play a huge role in reducing this oil import dependence (Abbas et al., 2023). One of the major constraints is that its yield remains lower than the estimated potential due to inefficient land utilization, increasing environmental constraints, and suboptimal crop management. That rises the need for the development of innovative production systems to uplift sunflower productivity and profitability and improve national acreage (Nungula et al., 2023).

Soybean and sunflower combination can help us fix several problems related to both of these crops. Both of these crops can be efficiently intercropped, as both crops exhibit distinct growth habits. For example, Sunflower produces a large canopy with a deep and vigorous root system; on the other hand, soybean develops a comparably shallow root system, a shorter stature, and it can also fix atmospheric nitrogen, as mentioned earlier (Shen et al., 2023; Puttha et al., 2023). All these variations lower the risk of direct competition for nutrients between crops, promoting harmonized utilization of essential resources like soil moisture and sunlight (Qiu et al.,2025). Moreover, soybeans make a dense canopy that can limit weed growth, while active fixation of atmospheric nitrogen improves the biological activity of soil, which further contributes to improved productivity of the whole cropping system (Kakabouki et al., 2022).

Multiple studies have shown that an organized, properly designed intercropping system enhances the land equivalent ratio (LER), biomass production of the entire system, water-use efficiency, nutrient-use efficiency, and economic profits compared to monocropping (Akchaya et al., 2025). Still, crop combinations, row arrangement, environmental conditions, and

planting geometry gravely affect the scale of these profits. Different spatial arrangements can change the competition for water, light, and nutrients even when the same component crops are cultivated, which results in huge differences in overall yield, system productivity, and crop growth (Nurgi et al., 2023).

The sunflower soybean intercropping system has been previously investigated around the world, showing positive results in most cases (Huzien et al., 2026), but the problem is that specific information about optimum row arrangements under the climatic conditions of Punjab, Pakistan, is still limited. Identifying the best intercropping pattern is important to enhance crop productivity, maximize land and resource use efficiency, and uplift farm profit rates under local conditions. So, further assessment of sunflower–soybean planting arrangements is required to recognize the most suitable cropping system (Bo et al., 2025).

The main goal of this study is to assess diverse sunflower soybean intercropping patterns under different cropping conditions and make a comparison between their effect on the grain yield and plant height of both crops under the agro-climatic conditions of Depalpur, District Okara, Pakistan. The hypothesis was that an optimized row-intercropping arrangement would improve grain yield and plant height compared with monocropping.

Materials and Methods

3.1 Experimental Site

The experiment was conducted at the Research Area of the University of Agriculture Faisalabad, Sub-campus Depalpur, District Okara, Pakistan, during the 2022 growing season of soybean-sunflower. The design of the study was made to assess the performance of multiple diverse soybean-sunflower intercropping schemes under different cropping systems, with respect to crop grain yield and plant height. The experimental site represents the semi-arid agroecological conditions of Punjab, where sunflower and soybean are important summer-season crops.

3.2 Weather Data

From August to December 2022, meteorological data, including relative humidity, minimum temperature, maximum temperature, and rainfall, were recorded. The Meteorological Station of Water Management, Renala Khurd, was the base from which the data were obtained and is located nearly 400m from the experimental area. Furthermore, the weather conditions are briefly mentioned in Figure 3.1

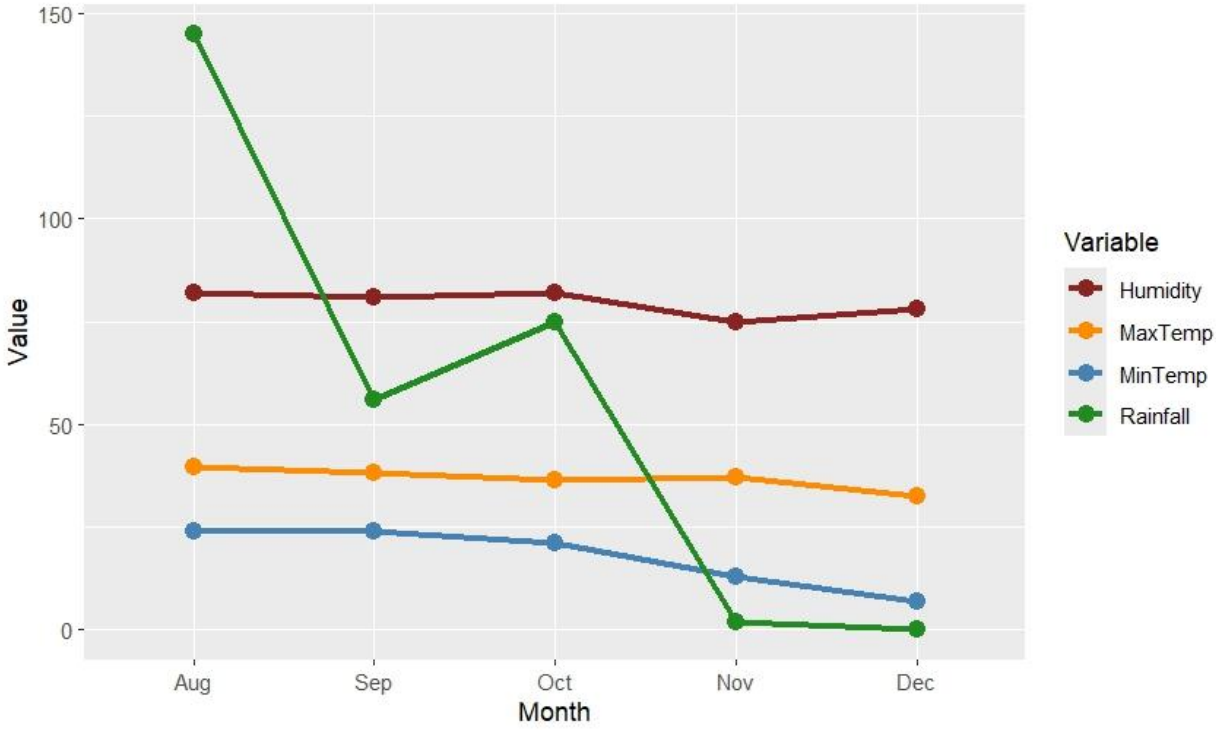


Figure 1 Graphical representation of Monthly rainfall, relative humidity, and maximum and minimum temperature from August to December 2022

3.3 Soil Analysis

Composite soil samples were collected before sowing from the experimental site from several representative locations at a depth of 0–30 cm. After that, following the standard procedures described by Chapman and Parker (1961), the collected samples were processed, air-dried, and analyzed for their physico-chemical properties. The soil characteristics of the experimental area are shown in Table 3.1.

Table 1: Physico-chemical properties of experimental site

Characteristics	Unit	Value
pH	NA	8.1
Organic matter	%	0.63
Total Nitrogen	%	0.024
Available phosphorus	mg kg^{-1}	7.3
EC	ds m^{-1}	1.3
Available potassium	mg kg^{-1}	160
Saturation percentage	%	35
Texture class	NA	Silty loam
Sand	%	18

Silt	%	55
Clay	%	27

3.4 Experimental Design and Treatments

A Randomized Complete Block Design (RCBD) with three replications was used for the experiment. 7 m × 6 m was the measurement of each experimental unit. Different cropping systems were used in this study, involving sole crops and sunflower–soybean intercropping patterns made under relay planting and simultaneous methods. Details of treatments are as follows:

1) T_1 Sole sunflower
2) T_2 Sole soybean
3) T_3 Sunflower –soybean (1:1) (Simultaneous Sowing)
4) T_4 Sunflower –soybean (1:2) (Simultaneous Sowing)
5) T_5 Sunflower –soybean (1:3) (Simultaneous Sowing)
6) T_6 Sunflower –soybean (1:1) (30 days relay planting of soybean)
7) T_7 Sunflower –soybean (1:2) (30 days relay planting of soybean)
8) T_8 Sunflower –soybean (1:3) (30-day relay planting of soybean)

3.5 Experimental Layout

In Figures 2 and 3, the complete field layout and the layout of a single experimental plot are illustrated, respectively.

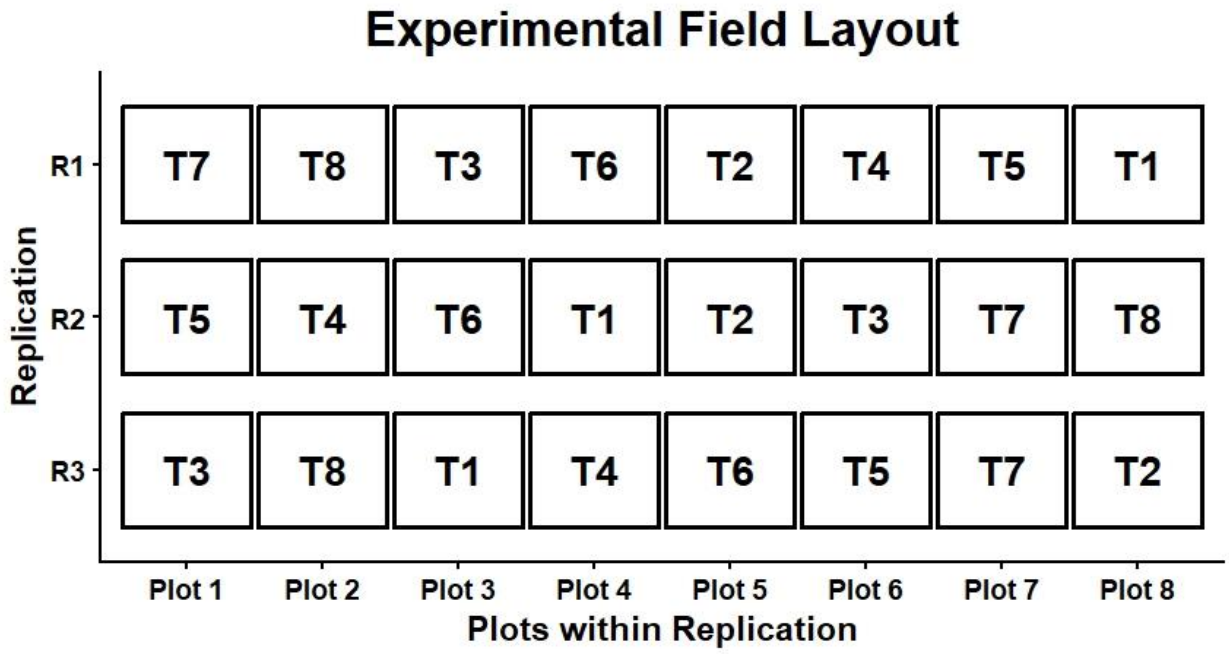


Figure 2 Field Layout

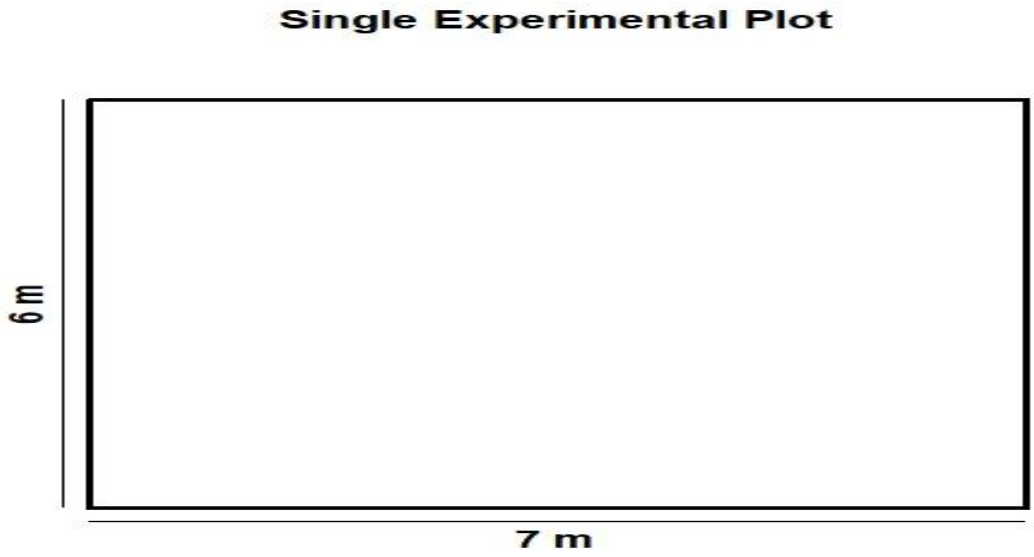


Figure 3

3.6 Crop Husbandry

3.6.1 Seedbed Preparation

At first, after harvesting the preceding crop, soaking irrigation (a pre-sowing irrigation practice) was done to aid proper site preparation. After reaching the optimum soil moisture level, the site was prepared by one disc ploughing, and after that, two to three cultivations were also done to obtain a perfect seedbed. A ridger was used to develop ridges before sowing.

3.6.2 Sowing

Faisal Soya, a famous cultivar in the Punjab region for soybean, and Hysun-33, a famous high-performing sunflower hybrid, were used in the studies. In August 2022, sowing was carried out based on the experimental treatments. Planting arrangements and sowing schedules were maintained according to the experimental design.

3.6.3 Fertilizer Application

Nitrogen (N), phosphorus (P), and potassium (K) fertilizers were applied according to their recommended doses for the specific land. Diammonium phosphate (DAP), sulphate of potash (50% K_2O), and Urea (46% N) were used as fertilizer sources and were uniformly applied to all the treatments. At sowing, the first split of nitrogen together with the full doses of phosphorus and potassium was applied, while the remaining nitrogen was applied according to the crop requirement.

3.6.4 Weed Management

Manual control of weeds through hand hoeing was done. A total of two hoeing operations were carried out during the crop growth and development period; the first was done at roughly 25

days after sowing, and the other one was at 60 days after sowing, to limit weed growth and competition for natural resources.

3.6.5 Pest Management

For pest management, throughout the cropping season, integrated pest management (IPM) practices were used. Sovicect insecticide was used to prevent Whitefly invasion roughly 20 days after planting. A mixture of Lufenuron, Emamectin benzoate, and Fipronil was used according to the recommended application rates to manage Fall armyworm. A follow-up application of Clothianidin was made approximately 55 days after planting to manage whitefly and other chewing insect pests.

3.6.6 Irrigation

According to crop water requirements, irrigation was applied in accordance with the weather conditions to make sure optimal crop growth and development throughout the experimental timeline.

3.6.7 Plant Protection

Thiophanate-methyl fungicide was used to treat seeds before sowing to protect them against soil and seed-borne diseases. During the crop season, protection measures, including insect pest, weed, and disease management, were done based on recommendations of the Agriculture Department to maintain optimum crop growth and development

3.6.8 Harvesting

Manual harvesting was done for both crops after they reached physiological maturity. Then the harvested plants were bundled and, to sun-dry them, they were placed in the open field, before they were subjected to threshing and further observations

3.7 Data Collection

Data were collected from all the experimental units following strict data collection rules and agronomic procedures. For the present study, data on grain yield and plant height were recorded to check the effect of intercropping on these traits

3.7.1 Grain Yield (Mg ha^{-1})

One representative row from each experimental unit was harvested at maturity; the heads were separated from the stalks, and the grains were hand-threshed and sun-dried. The grain yield was assessed in kilograms (kg) using an electronic weighing machine and later converted to megagrams per hectare (Mg ha^{-1}).

3.7.2 Plant height (%)

Five representative plants were randomly selected at maturity from each experimental unit. It was collected through measurements in centimeters (cm) using a measuring tape, hight was taken from the ground surface to the

At maturity, five representative plants were randomly selected from each experimental plot. Plant height was measured in centimeters using a measuring tape from the ground surface to the tip of the plant head. The measurements of the five plants were averaged to obtain the mean plant height for each plot.

3.8 Statistical Analysis

The recorded data were subjected to analysis of variance (ANOVA) appropriate for a Randomized Complete Block Design (RCBD). Treatment means were compared using the Least Significant Difference (LSD) test at the 5% probability level ($P \leq 0.05$) to determine significant differences among treatments.

4. Results

4.1 Grain yield

4.1.1 Sunflower

Grain yield of sunflower was significantly affected by the cropping patterns. Analysis of variance revealed a highly significant effect of treatments on sunflower achene yield ($F = 63.58$, $P < 0.001$), whereas the effect of replication was non-significant ($F = 0.58$). The treatment effect accounted for a substantial proportion of the observed variation in achene yield.

Mean comparison showed considerable variation among the cropping patterns. The highest achene yield was recorded in T3 (1669.33 kg ha^{-1}), which was significantly greater than all other cropping patterns. The sole sunflower treatment (T1) produced 1435.67 kg ha^{-1}, statistically similar to T6 (1380.33 kg ha^{-1}). The lowest achene yield was observed in T5 (1101.33 kg ha^{-1}). Treatments T4, T5, T7, and T8 formed the lower statistical group, with achene yields of 1121.00, 1101.33, 1151.67, and 1161.00 kg ha^{-1}, respectively.

Overall, the results indicated that sunflower productivity varied markedly with intercropping arrangement, with T3 producing the highest grain yield, whereas increasing the proportion of soybean relative to sunflower was associated with reduced sunflower achene yield under the evaluated cropping patterns.

Analysis of variance of grain yield of sunflower against different intercropping patterns.

SOV	DF	SS	MSS	F-value	P-value
Treatments	6	819578	136596	63.58	0.000*
Replication	2	2481	1240	0.58	
Error	12	25783	2149		
Total	20	847841			

*= Significant (P≤ 0.05) **=Highly significant (P≤ 0.01) ^{NS}=Non-significant (P> 0.05)

Mean comparison of grain yield of sunflower in different intercropping patterns.

Treatments	Grain yield (kgha^{-1})	Grouping
T5	1101.33	C
T8	1161.00	C
T4	1121.00	C
T3	1669.33	A
T1	1435.67	B
T6	1380.33	B
T7	1151.67	C

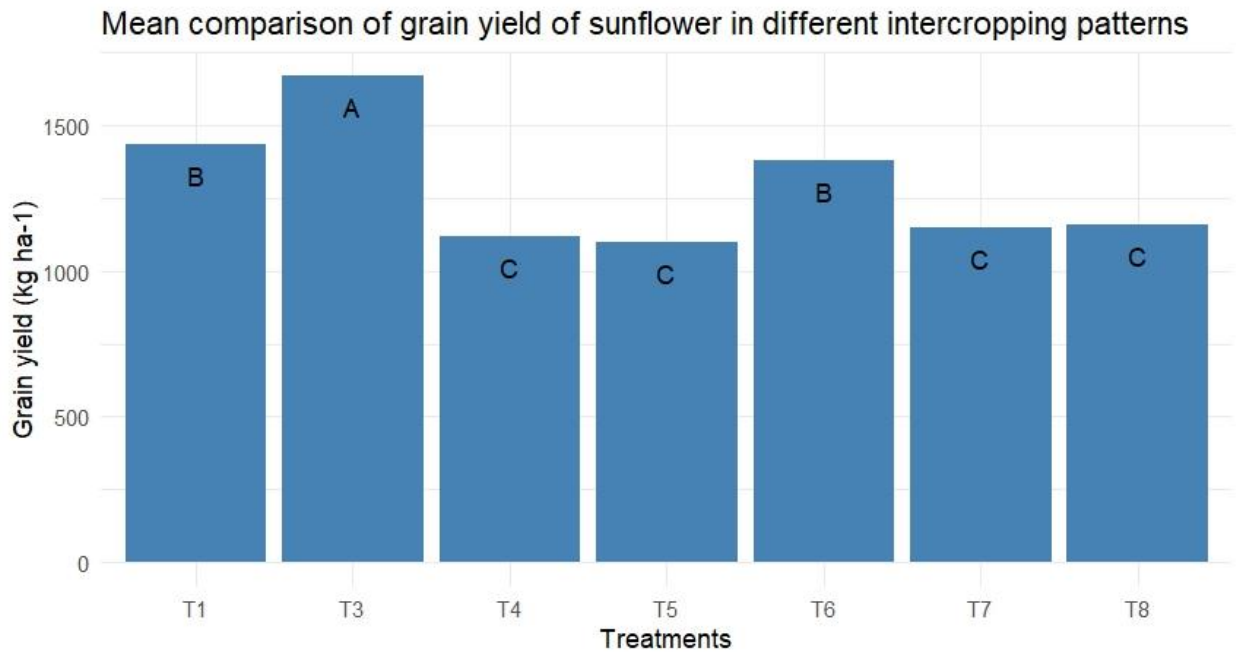


Figure 4 Mean comparison Plot for sunflower grain yield

4.1.2 Soya bean

Seed yield of soybean was significantly influenced by the different cropping patterns. Analysis of variance revealed a highly significant effect of treatments on soybean seed yield (F = 69.03,

$P < 0.001$), whereas the effect of replication was non-significant (F = 1.22). This indicates that the variation in soybean seed yield was primarily associated with the different cropping patterns rather than differences among replications.

The highest soybean seed yield was recorded in T3 (1351.67 kg ha^{-1}), followed by T2 (1285.67 kg ha^{-1}); both treatments belonged to the same statistical group (A), indicating that their yields were statistically comparable. The lowest seed yield was observed in T4 (970.33 kg ha^{-1}), which differed significantly from all other treatments. Seed yield under T8 (1158.67 kg ha^{-1}) was statistically lower than T2 and T3 but higher than T4. Treatments T5 (1083.67 kg ha^{-1}) and T7 (1097.33 kg ha^{-1}) were statistically similar, whereas T6 (1065.00 kg ha^{-1}) belonged to a significantly lower group than T5 and T7.

Overall, the results demonstrated that soybean seed yield varied substantially among the cropping patterns, with T3 producing the highest yield, while T4 resulted in the greatest reduction in soybean productivity.

Analysis of variance of grain yield of soybean against different intercropping patterns.

SOV	DF	SS	MSS	F-value	P-value
Treatments	6	316824	52804.0	69.03**	0.000
Replication	2	1861	930.3	1.22	
Error	12	9179	764.9		
Total	20	327863			

*= Significant (P≤ 0.05) **=Highly significant (P≤ 0.01) ^{NS}=Non-significant (P> 0.05)

Mean comparison of grain yield of soybean in different intercropping patterns.

Treatments	Grain yield (kgha^{-1})	Grouping
T2	1285.67	A
T8	1158.67	B
T3	1351.67	A
T4	970.33	D
T5	1083.67	BC
T7	1097.33	BC
T6	1065.00	C

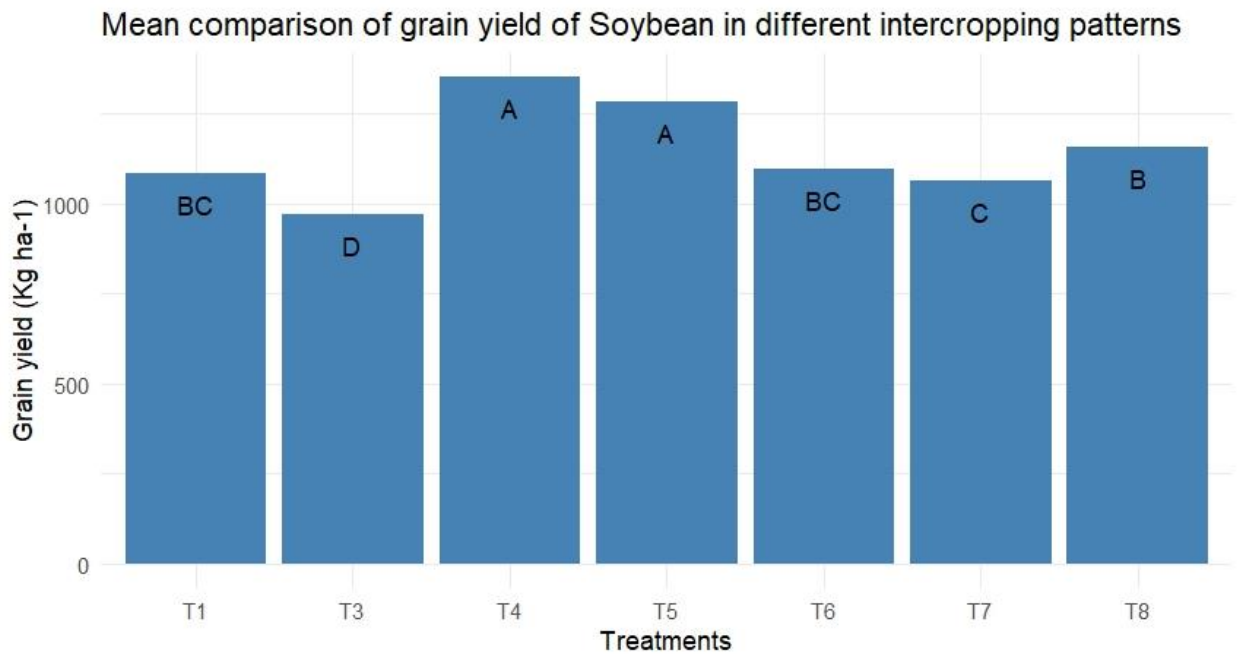


Figure 5. Mean Comparison of grain yield of soybean in different intercropping patterns

4.2 Plant Height

4.2.1 Sunflower

Plant height of sunflower differed significantly among the various intercropping patterns. Analysis of variance revealed a highly significant effect of treatments on sunflower plant height ($F = 40.00$, $P < 0.001$), while the effect of replication was non-significant ($F = 0.95$), indicating that variation in plant height was primarily driven by the cropping pattern rather than block effects.

Mean comparison showed that the tallest plants were recorded in T1 (136.71 cm), the sole sunflower treatment, which was statistically similar to T3 (134.04 cm). Treatments T6 (130.43 cm) and T7 (130.30 cm) formed an intermediate group, significantly shorter than T1 and T3 but taller than the remaining treatments. The shortest plants were observed in T8 (126.16 cm), statistically comparable to T4 (126.38 cm) and T5 (126.86 cm).

Overall, the results indicated that sole cropping and the 1:1 simultaneous sowing pattern (T3) favored greater sunflower plant height, whereas increasing the row proportion of soybean relative to sunflower, particularly under relay sowing, was associated with reduced plant height.

Table 4.1.7: Analysis of variance of plant height of sunflower against different intercropping patterns.

SOV	DF	SS	MSS	F-value	P-value
Treatments	6	320.239	53.373	40.00**	0.000
Replication	2	2.535	1.268	0.95	
Error	12	16.014	1.334		
Total	20	338.788			

*= Significant (P≤ 0.05) **=Highly significant (P≤ 0.01) NS=Non-significant (P> 0.05)

Table 4.1.8: Mean comparison of plant height of sunflower in different intercropping patterns.

Treatments	Plant height (cm)	Grouping
T1	136.71	A
T3	134.04	A
T6	130.43	B
T7	130.30	B
T5	126.86	C
T4	126.38	C
T8	126.16	C

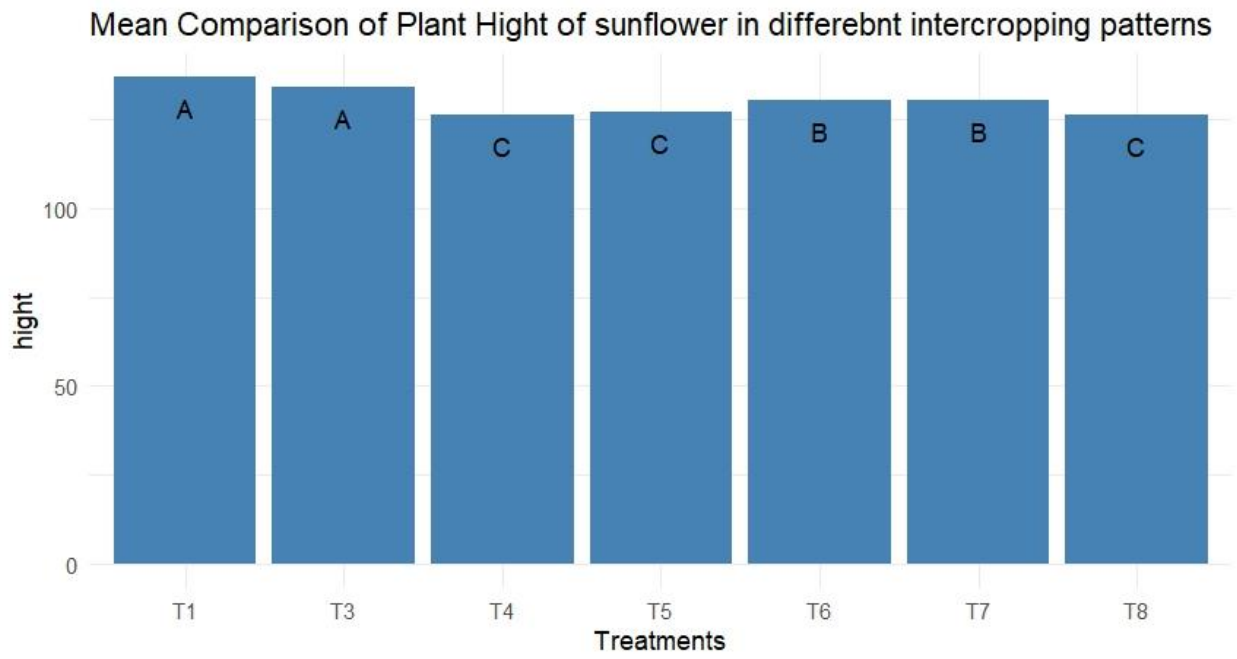


Figure 6. Mean comparison of Sunflower in different intercropping patterns

4.2.2 Soybean

Plant height of soybean was also significantly influenced by the different intercropping patterns. Analysis of variance showed a highly significant effect of treatments on soybean plant height ($F = 89.91$, $P < 0.001$), while the effect of replication was non-significant ($F = 0.67$), indicating that variation in plant height was mainly attributable to the cropping pattern rather than block differences.

Mean comparison revealed that the tallest soybean plants were recorded in T3 (87.98 cm), statistically similar to T8 (85.93 cm) and T2 (84.78 cm), which together formed the top-performing group. Plant height declined progressively through T5 (78.55 cm) and T4 (74.82 cm), which showed an overlapping intermediate response, followed by T7 (71.81 cm). The shortest plants were recorded in T6 (67.59 cm), which was significantly lower than all other treatments.

Overall, the results indicated that sole soybean cropping and the 1:3 arrangement under simultaneous sowing (T3) and relay sowing (T8) favored greater soybean plant height, whereas the 1:1 relay-sown pattern (T6) resulted in the most pronounced reduction in plant height

Table 4.2.11: Analysis of variance of plant height of soybean against different intercropping patterns.

SOV	DF	SS	MSS	F-value	P-value
Treatments	6	1084.12	180.686	89.91**	0.000
Replication	2	2.70	1.35	0.67	
Error	12	24.11	2.010		
Total	20	1110.93			

*= Significant (P≤ 0.05) **=Highly significant (P≤ 0.01) NS=Non-significant (P> 0.05)

Table 4.2.12: Mean comparison of plant height of soybean in different intercropping patterns.

Treatments	Plant height (cm)	Grouping
T3	87.98	A
T8	85.93	A
T2	84.78	A
T5	78.55	B
T4	74.82	BC
T7	71.81	C
T6	67.59	D

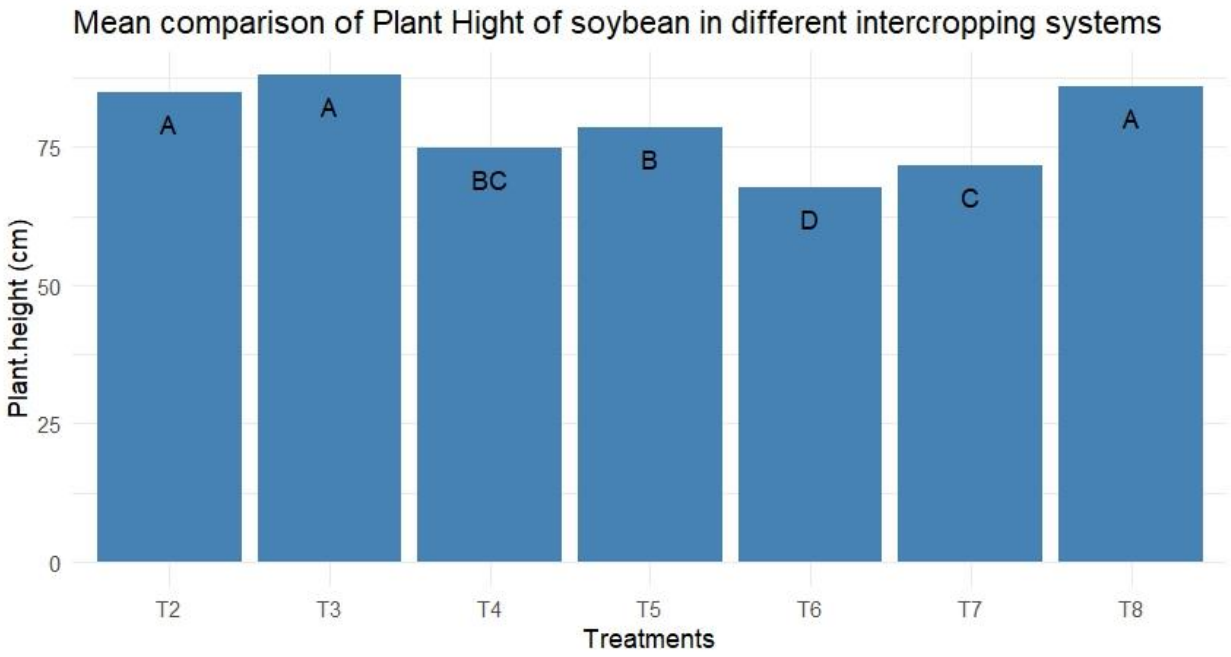


Figure 3 Mean Comparison of soybean in different inter cropping patterns

Discussion

5.1 Grain Yield

The results of the present study clearly demonstrated that the intercropping pattern had a pronounced influence on the grain yield of both sunflower and soybean. The 1:1 simultaneous sowing pattern (T3) consistently produced the highest yield in both crops, exceeding even the respective sole cropping treatments. This response can be attributed to the complementary growth habits of sunflower and soybean: the tall, deep-rooted sunflower and the shorter, shallow-rooted soybean occupy different vertical and horizontal niches within the same land area, allowing more efficient joint use of light, moisture, and nutrients than either crop could achieve alone. At the 1:1 ratio, the density of each component crop remains close to its optimal sole-crop population, minimizing intraspecific and interspecific competition while still allowing the system to benefit from complementary resource capture.

As the proportion of soybean rows increased relative to sunflower (1:2 and 1:3 arrangements, T4 and T5), sunflower yield declined progressively. This trend is consistent with increased competition for light and space near the crop margins, where a greater number of soybean rows likely intensified shading and root-zone competition on the sunflower plants adjacent to them, particularly given sunflower's requirement for full sunlight during head development and grain filling. Conversely, soybean yield under the wider row ratios (T4, T5) was also comparatively low, most likely because at these arrangements neither crop reached a population density

favorable to its own performance, resulting in a "lose-lose" competitive outcome rather than genuine complementarity.

Relay sowing of soybean 30 days after sunflower (T6, T7, T8) generally reduced yields of both crops compared with their simultaneous-sowing counterparts, with the exception of soybean yield under T8, which recovered somewhat at the widest row ratio. The reduction under relay sowing may be explained by the fact that by the time soybean was introduced, sunflower had already established a competitive advantage in canopy height and root development, placing the later-sown soybean at a disadvantage for light interception and moisture uptake during its critical early growth stages. This suggests that the timing of introduction of the companion crop is as influential on system yield as the spatial row arrangement itself.

Overall, these results support the broader principle that intercropping performance is governed by the balance between complementarity and competition, and that this balance is highly sensitive to both planting ratio and sowing time. The 1:1 simultaneous sowing pattern appears to represent the point at which complementary resource use was maximized while competitive effects were minimized for this sunflower–soybean combination under the agro-climatic conditions of Depalpur.

5.2 Plant Height

The plant height data reinforce the yield trends and provide further insight into the competitive dynamics operating within the intercropping system. Sole sunflower (T1) and the 1:1 simultaneous sowing pattern (T3) produced the tallest sunflower plants, with no significant difference between them, suggesting that at this row ratio, sunflower experienced minimal competitive restriction on its vegetative growth. In contrast, sunflower plant height declined under the relay-sown treatments (T6, T7, T8), which may reflect physiological stress or altered growth response associated with the staggered establishment of the companion crop, as well as possible microclimatic changes (e.g., altered humidity or light quality near the base of the canopy) introduced by the later-emerging soybean rows.

For soybean, plant height was tallest under sole cropping (T2) and the widest intercropping ratios (T3 and T8), where soybean plants may have exhibited a degree of etiolation or compensatory vertical growth in response to competition for light from the taller sunflower canopy, a common shade-avoidance response in leguminous crops grown in association with taller companion species. Notably, the shortest soybean plants were recorded under the 1:1 relay-sown treatment (T6), the same treatment associated with reduced grain yield, indicating that the combination of narrow row ratio and delayed sowing imposed the greatest overall competitive stress on soybean growth and development.

Taken together, the plant height results corroborate the yield findings and suggest that both spatial arrangement (row ratio) and temporal arrangement (simultaneous vs. relay sowing) jointly determine the extent of interspecific competition in sunflower–soybean intercropping systems. The consistency between plant height and yield responses across treatments strengthens the interpretation that light competition, more specifically the balance between canopy dominance by sunflower and compensatory or suppressed growth in soybean, was likely the primary mechanism underlying the observed treatment differences.

5.3 Overall System Performance

Collectively, the growth and yield responses observed in this study indicate that the 1:1 row ratio under simultaneous sowing (T3) offered the most favorable balance between the two component crops, achieving the highest yield in both sunflower and soybean without a corresponding yield penalty in either species. Wider row ratios (1:2, 1:3) and relay sowing generally shifted the competitive balance unfavorably, either suppressing sunflower performance through increased soybean density or suppressing soybean performance through delayed establishment relative to an already-competitive sunflower canopy. These findings underscore the importance of carefully matching planting geometry and sowing time to the specific growth habits of the component species when designing intercropping systems intended to maximize overall land productivity.

Conclusion

Based on the results of the present study, it is concluded that the sunflower–soybean intercropping pattern significantly influenced the growth and yield performance of both component crops. Among the evaluated cropping systems, the 1:1 row ratio under simultaneous sowing (T3) consistently produced the highest grain yield in both sunflower and soybean, along with favorable plant height in both species, indicating that this arrangement achieved the most efficient balance between complementary resource use and minimized interspecific competition. In contrast, wider row ratios (1:2 and 1:3) and relay sowing of soybean generally reduced the productivity of one or both component crops, reflecting an unfavorable shift in the competitive balance between the two species under these arrangements. Therefore, the 1:1 sunflower–soybean intercropping pattern under simultaneous sowing can be recommended as the optimum cropping system for enhancing the productivity of both crops under the agro-climatic conditions of Depalpur, District Okara, Punjab, Pakistan. Further studies incorporating land equivalent ratio and economic analysis are recommended to fully validate the agronomic and economic advantages of this intercropping system before wider recommendation to farmers.

References

Abbas, A., Mushtaq, Z., Ikram, A., Yousaf, K., & Zhao, C. (2023). Assessing the factors of economic and environmental inefficiency of sunflower production in Pakistan: An epsilon-based measure model. *Frontiers in Environmental Science, 11*, 1186328. https://doi.org/10.3389/fenvs.2023.1186328

Afzal, M. A., Shahzadi, N., Ijaz, M., Ali, M. A., & Saadat, S. (2025). Sustainable transformation road map to improved global food and nutrition security: a narrative review. *Frontier in Medical and Health Research*, *3*(6), 844-853. https://doi.org/10.5281/zenodo.16885883

Akchaya, K., Parasuraman, P., Pandian, K., Vijayakumar, S., Thirukumaran, K., Mustaffa, M. R. A. F., Rajpoot, S. K., & Choudhary, A. K. (2025). Boosting resource use efficiency, soil fertility, food security, ecosystem services, and climate resilience with legume intercropping: A review. *Frontiers in Sustainable Food Systems, 9*, 1527256. https://doi.org/10.3389/fsufs.2025.1527256

Bo, Y., Xing, Y., Liu, C., Shi, X., Liu, C., & Zhou, Y. (2025). Unveiling drivers and optimizing strategies for enhanced land and nitrogen fertilizer use efficiency of sorghum intercropping: A meta-analysis. *Field Crops Research, 332*, 110033. https://doi.org/10.1016/j.fcr.2025.110033

Cheriere, T., Lorin, M., & Corre-Hellou, G. (2023). Choosing the right associated crop species in soybean-based intercropping systems: Using a functional approach to understand crop growth dynamics. *Field Crops Research, 298*, 108964. https://doi.org/10.1016/j.fcr.2023.108964

Gardarin, A., Celette, F., Naudin, C., Piva, G., Valantin-Morison, M., Vrignon-Brenas, S., Verret, V., & Médiène, S. (2022). Intercropping with service crops provides multiple services in temperate arable systems: A review. *Agronomy for Sustainable Development, 42*, 39. https://doi.org/10.1007/s13593-022-00771-x

Guo, B., Sun, L., Jiang, S., Chen, Y., Wang, X., Chen, Y., & Zhang, J. (2022). Soybean genetic resources contributing to sustainable protein production. *Theoretical and Applied Genetics, 135*, 4095–4121. https://doi.org/10.1007/s00122-022-04222-9

Huzien, G. A. M., Harb, O. M. S., El-Aref, K. A. O., & Ahmed, M. A. (2026). Effect of intercropping soybean on sunflower and some fertilizer applications under conservation agriculture (CA) instructions. *Egyptian Journal of Agronomy, 48*(3), 1079–1091. https://doi.org/10.21608/AGRO.2026.457076.2034

Kakabouki, I., Mavroeidis, A., Kouneli, V., Karydogianni, S., Folina, A., Triantafyllidis, V., Efthimiadou, A., Roussis, I., Zotos, A., Kosma, C., & Katsenios, N. (2022). Effects of Nitrogen Fertilization on Weed Flora and Productivity of Soybean [*Glycine max* (L.) Merr.] Crop. *Nitrogen*, *3*(2), 284-297. https://doi.org/10.3390/nitrogen3020019

Kaur, S., Bedi, M., Singh, S., Kour, N., Bhatti, S. S., Bhatia, A., Kumar, M., & Kumar, R. (2024). Monoculture of crops: A challenge in attaining food security. In A. Sharma, M. Kumar, & P. Sharma (Eds.), *Advances in food security and sustainability* (Vol. 9, pp. 197–213). Elsevier. https://doi.org/10.1016/bs.af2s.2024.07.008

Nungula, E. Z., Mugwe, J., Nasar, J., Massawe, B. H. J., Karuma, A. N., Maitra, S., Seleiman, M. F., Dindaroglu, T., Khan, N., & Gitari, H. I. (2023). Land degradation unmasked as the key constraint in sunflower (*Helianthus annuus*) production: Role of GIS in revitalizing this vital sector. *Cogent Food & Agriculture, 9*(2), 2267863. https://doi.org/10.1080/23311932.2023.2267863

Nurgi, N., Tana, T., Dechassa, N., Tesso, B., & Alemayehu, Y. (2023). Effect of spatial arrangement of faba bean variety intercropping with maize on yield and yield components of the crops. *Heliyon, 9*(6), e16751. https://doi.org/10.1016/j.heliyon.2023.e16751

Okolie, C. C., Danso-Abbeam, G., Groupson-Paul, O., & Ogundeji, A. A. (2023). Climate-Smart Agriculture Amidst Climate Change to Enhance Agricultural Production: A Bibliometric Analysis. *Land*, *12*(1), 50. https://doi.org/10.3390/land12010050

Pandit, M., Panthi, S., & Chiluwal, A. (2026). Biological Nitrogen Fixation in Soybean: Mechanisms, Benefits, Sustainability, and Future Prospects. *Agronomy*, *16*(10), 946. https://doi.org/10.3390/agronomy16100946

Petrenko, V., Topalov, A., Khudolii, L., Honcharuk, Y., & Bondar, V. (2023). Profiling and geographical distribution of seed oil content of sunflower in Ukraine. *Oil Crop Science, 8*(2), 111–120. https://doi.org/10.1016/j.ocsci.2023.05.002

Puttha, R., Venkatachalam, K., Hanpakdeesakul, S., Wongsa, J., Parametthanuwat, T., Srean, P., Pakeechai, K., & Charoenphun, N. (2023). Exploring the Potential of Sunflowers: Agronomy, Applications, and Opportunities within Bio-Circular-Green Economy. *Horticulturae*, *9*(10), 1079. https://doi.org/10.3390/horticulturae9101079

Qiu, Y., Wang, Z., Sun, D., Lei, Y., Li, Z., & Zheng, Y. (2025). Advances in Water and Nitrogen Management for Intercropping Systems: Crop Growth and Soil Environment. *Agronomy*, *15*(8), 2000. https://doi.org/10.3390/agronomy15082000

Quintarelli, V., Radicetti, E., Allevato, E., Stazi, S. R., Haider, G., Abideen, Z., Bibi, S., Jamal, A., & Mancinelli, R. (2022). Cover Crops for Sustainable Cropping Systems: A Review. *Agriculture*, *12*(12), 2076. https://doi.org/10.3390/agriculture12122076

Raza, M. A., Zhiqi, W., Yasin, H. S., Gul, H., Qin, R., Rehman, S. U., Mahmood, A., Iqbal, Z., Ahmed, Z., Luo, S., Juan, C., Liang, X., Gitari, H. I., Bin Khalid, M. H., Feng, Y., & Zhongming, M. (2023). Effect of crop combination on yield performance, nutrient uptake, and land use advantage of cereal/legume intercropping systems. *Field Crops Research, 304*, 109144. https://doi.org/10.1016/j.fcr.2023.109144

Shen, L., Wang, X., Liu, T., Wei, W., Zhang, S., Zhu, Y., Tuerti, T., Li, L., & Zhang, W. (2023). Apple–Soybean Mixed Stand Increased Fine Root Distribution and Soil Water Content with Reduced Soil Nitrate Nitrogen. *Agronomy*, *13*(2), 548. https://doi.org/10.3390/agronomy13020548

Te, X., Din, A. M. U., Cui, K., Raza, M. A., Fraz-Ali, M., & Xiao, J. (2023). Inter-specific root interactions and water use efficiency of maize/soybean relay strip intercropping. *Field Crops Research, 291*, 108793. https://doi.org/10.1016/j.fcr.2022.108793