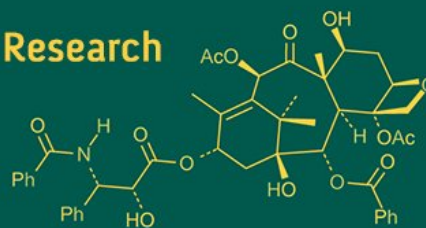


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Effect of row arrangement on productivity and resource use efficiency in pea-barley intercropping systems: A comprehensive review

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Abstract

The intercropping of pea and barley has been an object of great interest in recent years for its production potential, as well as its high efficiency in the use of resources and environmental sustainability. The impact of row arrangement on productivity and resource-use efficiency of intercropping pea-barley systems is critically discussed. This study combines the results of the pea-barley and related cereal-legume intercropping studies on yield performance, land-use efficiency, radiation-use efficiency, water-use efficiency, nutrient-use efficiency, and energy-use efficiency and those obtained under different spatial arrangement and row ratios. Based on the literature reviewed, it has been concluded that the balanced row systems (1:1 alternate rows, 2:1, and strip intercropping systems) perform better in terms of productivity and utilization of the resources than the mixed sowing or monocropping systems. The improved performance is primarily due to complementary interactions of pea and barley in canopy structure and rooting pattern, nutrient uptake, and biological nitrogen fixation. The review also puts into perspective the major limitations such as mechanization challenges, unreliable interspecific competition under stress situation, and scarcity of long-term precision and climate smart intercropping studies. Future research should be directed towards optimizing spatial configuration, incorporating technologies of precision agriculture and establishing resilient intercropping systems for sustainable intensification in response to climate change.

Keywords: Pea-barley intercropping, row arrangement, resource-use efficiency, land equivalent ratio, cereal-legume intercropping

Introduction

Legume - cereal intercropping is gaining popularity as an essential practice for sustainable and climate smart agriculture that can not only ensure yield maintenance but also increase yields without the need for external inputs and environmental impacts. Legume intercropping can boost main crop equivalent yields by approximately 30-35%, water use efficiency by 20-25%, nutrient use efficiency by 25-30%, and reduce pest and disease losses by 20-25% compared to monocropping, which also contributes about 125 kgN ha⁻¹ season⁻¹ (Akchaya et al., 2025) [2]. The results of a global meta-analysis of 462 field experiments showed that average subsequent crop production gains were ~20% in legume-based systems, significantly higher (32%) in low input, low yield areas, highlighting the potential of legumes to enhance ecological intensification and food security (Zhao et al., 2022) [47]. In a broader context, cereal- legume intercrops performed better in terms of land equivalent ratios >1 in low P, semi-arid Mediterranean soil, greater N and P uptake in the rhizosphere and superior grain yield compared with sole crops, resulting in more efficient use of limiting resources (Brahimi et al., 2022) [6]. In the pea-barley system, pea-barley strip till row intercropping (alternate rows of pea and barley) resulted in a 8-10% increase in the productivity (yields) of both species and a greater than 40% increase in pea productivity than with within row mixing, and reduced weed infestation, particularly highlighting the importance of the row arrangement and spatial configuration in reducing competition and enhancing compatibility (Jaskulska et al., 2022) [15]. Although the number of cereal-legume intercropping papers is small (4,732), topic modelling reveals that global research interest is increasing quickly, with crop yield and N fixation as the major topics and a rise in interest in climate resilience, sustainability and ecosystem services, while socio-economic barriers and

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species selection are identified as topics that have limited research. (Landschoot *et al.*, 2024) ^[22].

Principles and Concepts of Intercropping

Intercropping is generally considered as the intentional cultivation of two or more crop species or genotypes in one field for a significant portion of their growing period with sufficient overlap in space and/or time and interacting ecologically, as opposed to the simple crop rotation (Toker *et al.*, 2024; Anchal *et al.*, 2025) ^[43, 50]. Spatially speaking, systems can be categorized as row, strip, or mixed systems, and temporally as simultaneous, relay, or additive/replacement systems, depending on the nature of the system (Toker *et al.*, 2024; Anchal *et al.*, 2025; Datta *et al.*, 2025) ^[8, 43, 50]. Total crop density in additive series is kept and the addition of the companion crop is added, thus total plant density increases; total plant density in replacement series remains the same, with the two crops being substituted one after the other in fixed proportions (Anchal *et al.*, 2025; Ruillé *et al.*, 2026) ^[39, 50]. The balance of interspecific and intraspecific competition depends on the design; so does the size of intercrop advantages. Intercrop performance lies on a continuum from competition (for light, water, and nutrients) to facilitation (*e.g.* Nu_2 fixation, microclimate amelioration, pest suppression). *Ecological meta*-analyses reveal that, on average, intercropping can boost the productivity of land by approximately 20-30%, compared to monocultures, although there are significant variations in the nature of these interactions, ranging from strong overyielding to yield loss, suggesting strong context dependence of these interactions (Mac Laren *et al.*, 2023; Li *et al.*, 2023) ^[24, 28]. In cereal-legume systems, facilitation is especially associated with the access of legumes to Nu_2 in the air, which reduces competition for soil N, increases N available in the rhizosphere, and in some cases, transfers 17-43% of fixed N to the cereal component, resulting in higher LERs (Brahimi *et al.*, 2022; Salinas-Roco *et al.*, 2024; Gungaabayar *et al.*, 2022) ^[6, 12, 40]. Spatial and temporal complementarity are fundamental concepts to explain resource-use efficiency. Canopy height and leaf area and rooting depth differences divide resources across space, while contrasting phenology and growth rates reduce peaks in resource demand across time (Mac Laren *et al.*, 2023; Toker *et al.*, 2024; Li *et al.*, 2023; Wu *et al.*, 2022) ^[24, 28, 43, 45]. From a global analysis, several levers emerge: benefits are usually observed when the density reduction of a component species in a mixture is offset by complementarity in the use of light and nutrients, so that the partial LERs of component species add up to values >1 for mixtures, even for lower densities of those species (Ruillé *et al.*, 2026) ^[39]. In semi-arid cereal-legume systems, this complementarity has been proven to enhance nodulation by $\sim 32\%$, grain yield and N and P uptake, and the LER always has been higher than the monocrop (Brahimi *et al.*, 2022) ^[6]. In addition, intercropping also affects belowground ecology, including the diversity of microorganisms, N transformation and distribution, which contributes to continuous N supply and decreased reliance on fertilizers (Lai *et al.*, 2022; Rahman *et al.*, 2025) ^[36, 21]. Meanwhile, it has been revealed that competition is still a key mechanism: when there is reduced competitive pressure of dominant species on subordinates, yield is maximized; as well as by complementarity effects (not by selecting a single high yielding species), particularly for water and N (Wu *et al.*,

2022) ^[45]. These principles give a conceptual background to pea-barley intercropping: the densities and row spacings must be suitable and sowing times optimized to reduce asymmetric competition as much as possible while maximizing light, water and nitrogen complementarity, explaining the reported productivity and resource-use efficiency increases in cereal-legume systems (Mac Laren *et al.*, 2023, Brahimi *et al.*, 2022, Li *et al.*, 2023, Ruillé *et al.*, 2026, Wu *et al.*, 2022) ^[6, 24, 28, 39, 45].

Agronomic and Physiological Compatibility of Pea and Barley

Agronomic and physiological compatibility of pea and barley is based on complementary traits related to rooting, canopy development, phenology and N acquisition that enable more efficient utilization of environment resources than monocrops. Cereals are usually the dominant biomass component (65-92% of total dry matter) in pea-barley forage systems but intercropping leads to a 25-118% forage yield increase over pea monocrop across sites, and pea also provides biologically fixed N and N transfer to barley (Gungaabayar *et al.*, 2022) ^[12]. N fixing ability of Pea alone with Rhizobium is $\sim 200 \text{ kg N ha}^{-1}$ and N fixation in intercrops of $\sim$ pea with barley/oat ranged from 18 to 59 kg N ha^{-1} ; belowground complementarity in N $^{-}$ acquisition was evident as 17-43% of the fixed N was transferred to the cereal component (Gungaabayar *et al.*, 2022) ^[12]. Western Canadian intercropping reviews show that pea-barley supports more pea nodulation ($\sim 45\%$ more than intercropped pea), which yields an added contribution of $> 60 \text{ kg N ha}^{-1}$ to the system, while also enhancing grain and forage quality $^{-}$ and N recovery (Mbanyeleye *et al.*, 2024) ^[31]. These benefits stem from contrasting root structures and nutritional strategies: peas invest in deep rooting and capturing Nu_2 from the air, while barley's dense fibrous roots quickly consume mineral N, resulting in less Nu_2 fixation inhibition and a boost in total N capture (Brahimi *et al.*, 2022; Salinas-Roco *et al.*, 2024; Gungaabayar *et al.*, 2022) ^[6, 12, 40]. Spatial and temporal niche differentiation is caused by differences in canopy architecture and phenology (shorter, more erect cereals vs. vining peas, and different maturity time). Phenological and morphological characteristics like the number of days to maturity, plant height, and growth habit have a significant effect on light interception and overyielding in the mixtures (mean LER of ~ 1.24 - 1.26 in cereal-pea intercrops for specific barley-pea combinations, such as the long-straw or determinate pea, and shorter cereals) (Demie *et al.*, 2022) ^[9]. Additionally, experiments on winter wheat-pea mixtures demonstrate that earlier or autumn sowing can help to reduce the time interval to establishment, boost early crop development rates, improve soil cover and biomass production, and boost yield advantages ($\text{LER} > 1$) by 10-14% (Neugschwandtner *et al.*, 2025) ^[33], thereby illustrating how phenology and canopy dynamics shape competition- complementarity balances over time. These insights are extended by recent mechanistic and modelling work, which showed that the relative advantage of intercrop overyielding is high at low levels of N and P availability (*e.g.*, when LER for N and P uptake is 1.35-1.66 under these conditions), and that facilitative interactions (*e.g.*, enhanced rhizosphere nutrient availability around legumes) are more pronounced at low nutrient inputs, whereas high inputs tend to diminish these relative advantages (Brahimi *et al.*, 2022; Zhu *et al.*, 2023) ^[6, 49]. The gains in pea-barley intercrop productivity and

resource-use efficiency documented are well reproduced by process-based models parameterized for pea-barley and other cereal-legume mixtures, which are realistic in their ability to simulate leaf area, biomass, N and water balances (normalized RMSE ~18-25%), supporting the interpretation of the importance of multi-resource complementarity in rooting depth, canopy stratification, N fixation and nutrient uptake timing.

Concept and Importance of Row Arrangement in Intercropping

The arrangement of rows is one of the fundamental design considerations in cereal-legume intercropping systems as it determines the way the different species compete, facilitate and occupy physical space and resources (light, water, nutrients and space) and therefore influences the possibility of mechanised management. In the pea-barley and associated systems, the spatial configuration can vary from alternate single row and double row to multirow type strip intercropping with specified row ratios and strip widths. The yield benefits of intercropping has been repeatedly found to be not just due to species choice, but to row configuration. For instance, pea-barley strip till row intercropping with strict alternate row planting with barley and pea resulted in higher uniformity of emergence, yield of pea and barley plants and lower weed infestation than did the mixed withing row planting of pea- barley seeds, and increased yield of barley and pea by 8.5 and 10.2% over sole cropping (Jaskulska *et al.*)^[15]. Maize-soybean and maize-peanut strip systems have shown that certain ratios of maize to soybean or peanut rows with border row maize (2 maize:4 soybean or 4 maize:8 peanuts) are optimal to maximize system yield and LER, balancing the border row advantage of the tall cereal with adequate light availability for the shorter legume (Kou *et al.*; Lu *et al.*; Jin *et al.*; Kou *et al.*). The width of the legume strips or their row configuration can increase legume light interception by more than 40% and legume yield by approximately 25- 30%, but too wide or too many legumes will decrease the light capture and yield of maize, resulting in intermediate legume ratio (*e.g.* 2M4S) often providing the highest total grain yield and land equivalent ratio (LER up to ~1.6) (Jin *et al.*; Kou *et al.*). Narrow strips of soybean in wheat-soybean relay intercropping reduced the size of the crop (dry matter) of both wheat and soybean by up to 58% and 34%, respectively, as compared with wider strips, and caused a decrease in LER and profit by 24% and 34%, respectively, mostly due to increased shading and belowground competition (Raza *et al.*). Optimized maize-soybean densities within a fixed strip pattern also had a positive effect on grain production over both sole crops and improved water and N use efficiency, suggesting that row pattern and density need to be co designed (Li *et al.*; Raza *et al.*). Alternate or narrow strips maximized light capture by the border rows, while wider or multi row strips affected vertical light gradients and diurnal light distribution, which were closely linked to cumulative intercepted PAR, light use efficiency and yield of both species in maize-soybean crops (Kou *et al.*; Jin *et al.*). Root patterns belowground affect N uptake and root-root competition, with feedback to N facilitation in cereal-legume cropping systems, but there is relatively little explicit data on root pattern. Row and strip layouts have implications for both management and mechanization; from a management point of view, row and strip layouts determine which combinations of field

Different row ratios and system productivity

operations and crops can be adopted to achieve both high yields and compatibility with a range of existing machines (Thinley *et al.* 170 - 184; Zheng *et al.*; Kou *et al.*). Modelling and meta regression studies also indicate that 1:1 arrangements of alternate rows and moderate cereal dominance (67%, 33-50% cereal: legume) achieve optimal cereal yield and weed control, while mixed and within row arrangements increase interspecific competition and species dominance, potentially reducing the yield of the weaker species (Gu *et al.* 2234 - 2247; Lebreton *et al.*). All this evidence suggests that the “concept” of row arrangement should be viewed as a key tool to tune the above- and below-ground competition-complementarity relationships, light interception, resource use efficiency and operational feasibility in pea-barley intercropping; accordingly, careful selection of row arrangement between alternate rows, paired/strip rows, and row ratios is important in the design of productive and mechanization ready pea-barley intercropping systems.

Effect of Row Arrangement on Yield and Yield Attributes

Row Arrangement Effects on Yield and Yield Attributes in Pea-Barley Intercropping

The site arrangement greatly influences the way pea and barley make use of complementarity to produce grain yields and biomass, and system-level productivity. Studies with pea-barley and similar barley-legume and cereal-legume combinations have shown that the alternate row and well-balanced strip method of culture can frequently give greater yield and economics than the mixed sowing or unbalanced ratios of row or strip cultures.

Grain and Biomass Yield, Harvest Index

Jaskulska *et al.* (2022)^[15] compared 1:1 alternate rows (row intercropping) with sole barley and pea crops in a 3 years trial and found that the former was 8.5% and 10.2% effective in the increase of barley and pea productivity, respectively, over the sole crops, and that pea yield in 1:1 alternate rows was 38.9% higher than in mixed within row sowing. The combined grain/seed yield in intercrop was 1.75 t ha⁻¹ higher than in pure pea, but 0.79 t ha⁻¹ lower than in pure barley; the yield of total protein was equal to pure pea and higher than pure barley by 109 kg ha⁻¹ (Jaskulska *et al.*, 2022)^[15].

Intercropping of barley with field pea was done at different ratio of the row numbers (3:3 to 6:6); 6:6 and 5:5 row numbers produced the highest system productivity: barley grain yield in 6:6 was equal to 5:5 and significantly higher than other ratios and barley-linseed mixtures (Neelam *et al.*, 2025)^[32]. Maximum barley equivalent yields of 71.37 and 66.09 q ha⁻¹ were obtained in the same treatments as compared to other cropping systems such as sole crops (Neelam *et al.*, 2025)^[32] which were 7.98-55.8% lower. The yield of both crops in toria-field pea 3:3 intercropping (12.0 and 10.6 q ha⁻¹) and harvest index of pea (44.7%) was the highest indicating that the symmetrical ratios of row configuration may be beneficial to both biomass partitioning and economic returns (Ali *et al.*, 2022)^[3]. Across a range of sowing ratios, wheat- pea intercrops yielded 10-14% higher than wheat monocrops (LER > 1), indicating that the promotion of appropriate spatial-temporal balance, creates higher final biomass and grain production (Neugschwandtner *et al.*, 2025)^[33].

System & Crop Pair	Best Row Arrangement	Key Yield / Productivity Outcomes	Citations
Pea-barley (grain/protein)	1barley:1pea (alternate rows)	+8.5% barley and +10.2% pea productivity vs. sole; pea +38.9% vs. mixed sowing	(Jaskulska et al., 2022) ^[15]
Barley-field pea (grain)	6:6 (≈1:1) and 5:5	Barley 32.67 q ha ⁻¹ ; BEY 71.37-66.09 q ha ⁻¹ , up to +55.8% vs. sole crops	(Neelam et al., 2025) ^[32]
Maize-alfalfa	2:2	Cumulative yield 55-57% > either monocrop; LER and SPI highest	(Shao et al., 2025) ^[41]
Maize-soybean	2:4 (narrow strips)	LER 1.59; group yield +10.4% vs. other layouts	(Feng et al., 2022) ^[10]
Maize-faba bean	1:1	LER 1.268 (≈27% yield advantage); highest maize equivalent yield	(Nurgi et al., 2023) ^[34]

These consistent responses indicate that intermediate, near-balanced row ratios (1:1; 2:2; symmetric strips) often maximize total system productivity, even where the cereal remains the dominant grain producer.

Yield Attributes: Pods, Tillers, Spikes, and Harvest Index

Specific pea and barley traits respond to row arrangement. In strip-till pea-barley, alternate rows improved pea plant density at harvest, which underpinned the 38.9% pea yield gain vs. mixed within-row sowing (Jaskulska *et al.*, 2022) ^[15]. While pod number is not explicitly quantified, increased density and reduced weed pressure likely enhanced pod formation and seed set per unit area (Jaskulska *et al.*, 2022) ^[15].

In barley-field pea systems, barley yield attributes were highest in sole barley but remained high under the best intercrop arrangements: barley tillers reached 488.8 m² in sole crop, only ~ 29.2 m² more than in 6:6 barley+pea; tillers, test weight (47.4 g in sole barley) and grains ~ per ear all correlated strongly with grain yield (*r* = 0.887, 0.903 and 0.722 respectively, *p* ≤ 0.05-0.01), explaining 54-64% of variation in barley equivalent yield (Neelam *et al.*, 2025) ^[32]. Intercropping therefore slightly reduces individual barley tillering and grain weight but can increase system-level equivalent yield when rows are appropriately balanced.

In the toria-field pea 3:3 system, both crops showed maximum branches, pods per plant and test weight, and field pea’s harvest index rose to 44.7% compared with 37.8% in less favorable 1:3 arrangements (Ali *et al.*, 2022) ^[3]. This supports the interpretation that balanced row geometries improve reproductive allocation (HI) in the legume and stabilize cereal yield attributes.

Barley-field bean alternate rows in an additive design showed clear cropping system × N rate interactions: increasing N raised barley grain yield by +260% in monocrop vs. only +56% in intercrop, and at high N barley monocrop grain yield was 4.6-fold that of intercropped barley (Pampana *et al.*, 2022) ^[35]. Above-ground biomass and grains per spike were similarly depressed under intercropping at high N (Pampana *et al.*, 2022) ^[35]. These results indicate that row-based intercrops can restrict per-plant yield attributes of cereals under high fertility, reinforcing the need to tune both spatial pattern and input level.

Total System and Equivalent Yields under Different Arrangements

Several studies quantified total system productivity using barley equivalent yield, maize equivalent yield, or cumulative system yield. In barley-field pea systems, 6:6

and 5:5 rows achieved the highest BEY (71.37 and 66.09 q ha⁻¹), outperforming sole barley, sole pea and ~ all barley-linseed intercrops (Neelam *et al.*, 2025) ^[32]. Yield advantages of the best barley+pea ratio over alternatives ranged from 7.98% to 55.79% (Neelam *et al.*, 2025) ^[32].

In maize-alfalfa, a 2:2 row ratio produced cumulative yields of 14.7-15.4 t ha⁻¹, 55-57% ~ higher than either monocrop, with the highest LER, land equivalent coefficient and system productivity index, and more balanced competition compared with maize-dominated 3:1 or 3:2 (Shao *et al.*, 2025) ^[41].

Maize-faba bean 1:1 intercropping delivered a maize equivalent yield of 6.28 t ha⁻¹, LER ~ 1.268 and a 26.8% yield advantage, clearly exceeding 1:2 or 2:2 arrangements for system output (Nurgi *et al.*, 2023) ^[34]. Similar patterns appear in maize-soybean strip systems, where 2.4 m bands with a 2:4 row ratio gave LER 1.59 and group yield increases of 7.6-10.4% over 2:3 (Feng *et al.*, 2022) ^[10].

These data, combined with modelling work on barley-pea and other cereal-legume mixtures showing reliable simulation of grain yield (*nRMSE* ~18%) across contrasting sowing patterns (Vezy *et al.*, 2023) ^[44], support a general conclusion: symmetric or moderately legume-enriched row ratios (1:1, 2:2, 6:6, 5:5; or 2:4 in narrow strips) tend to maximize equivalent yield and LER, provided total plant density is not excessive.

Implications for Identifying Optimum Row Arrangements in Pea-Barley

Direct pea-barley evidence identifies 1:1 alternate rows under strip-till as more productive than both sole crops and within-row mixing, with notable gains in pea yield and system protein production (Jaskulska *et al.*, 2022) ^[15]. Barley-field pea work under irrigated conditions points to 6:6 and 5:5 equal-row arrangements as the most productive in terms of barley grain and barley equivalent yields, with strong positive correlations between barley yield attributes and overall system productivity (Neelam *et al.*, 2025) ^[32].

Converging evidence from wheat-pea and barley-pea simulations and multiple cereal- legume systems indicates that these outcomes are not crop-specific anomalies but expressions of shared mechanisms: improved light capture by both species, reduced extreme dominance by the cereal, and better expression of the legume’s reproductive potential and harvest index at intermediate, balanced row ratios (Jaskulska *et al.*, 2022; Shao *et al.*, 2025; Neelam *et al.*, 2025; Lebreton *et al.*, 2024; Feng *et al.*, 2022; Vezy *et al.*, 2023) ^[44, 10, 23, 32, 41, 15].

Overall, the most productive row arrangements for pea-barley intercropping 1:1 alternate rows in mechanized strip-till and approximately equal row numbers (5:5 or 6:6) in broader strips consistently increase total grain or forage

yield, equivalent yield, and often harvest index of pea, while maintaining acceptable barley tillering and spike performance.

Resource Use Efficiency in Pea-Barley Intercropping Systems

Intercropping systems are known to be more efficient in resource use than monocropping because they utilize environmental resources in a complementary way, including light, water, nutrients and space. Legumes enhance soil fertility by fixing N, while cereals use soil nutrients and radiation resources to the maximum level with higher system productivity and sustainability (Lithourgidis *et al.*, 2011; Bedoussac *et al.*, 2015; Martin-Guay *et al.*, 2018) [26, 5, 30]. The pea-barley intercropping is an important cereal-legume system in temperate and semiarid agroecosystems that can boost the productivity by minimizing external inputs. The arrangement of rows and space configuration have significant effects on resource complementarity and competitive interactions between component crops (Brooker *et al.*, 2015) [7].

Land Use Efficiency

One of the main indicators for assessing the biological benefits of intercropping systems is land-use efficiency. Land Equivalent Ratio (LER) values above 1 imply that intercrops are more efficient in utilizing land resources than sole crops. There are several studies on cereal-legume intercropping that have reported LER values between 1.10 and 1.45, indicating a considerable productivity advantage over the monoculture systems (Lithourgidis *et al.*, 2011; Bedoussac *et al.*, 2015) [5, 26]. Row arrangements, which are common in pea-barley and other cereal-legume crops, often led to higher LER and Area Time Equivalent Ratio (ATER) values than sole cropping (Hauggaard-Nielsen *et al.*, 2008) [14]. The intercropping patterns of strips were frequently found to be more productive than the mixed intercropping systems as the light transmittance was better and there was less interspecific competition (Yu *et al.*, 2015) [46]. Alternate-row planting also improved total biomass productivity in wheat-pea and barley-faba bean systems, as shown by research (Bedoussac & Justes, 2010) [4]. The increased land-use efficiency of intercrops is mainly due differential use of environmental resources. Cereals quickly invade upper layers of the canopy space and efficiently intercept solar radiation and legumes occupy lower canopy space, and provide added nitrogen by symbiotic fixation (Brooker *et al.*, 2015) [7]. There is also less direct competition because of variations in rooting depth and nutrient uptake strategies that lead to higher overall productivity (Jensen *et al.*, 2020) [16]. ATER values are especially helpful when dealing with multiple crops with different growth periods. It has been established that a well-designed row layout results in a higher use of land resources during the growing season (Lithourgidis *et al.*, 2011) [26]. Too big a cereal density, however, has been shown to inhibit legumes growth and limit intercrop advantages, so balanced row proportions are important (Bedoussac *et al.*, 2015) [5]. Although there is a large body of evidence showing an increase in land-use efficiency in cereal-legume cropping systems, relatively little research has specifically investigated pea-barley intercropping in a variety of agroecological environments. Optimization of row arrangement in order to obtain the highest land productivity

requires long-term investigations combining precision agriculture and spatial modelling approaches.

Radiation Use Efficiency

In intercropping system, radiation-use efficiency (RUE) is the most important factor for biomass production and yield. Cereal-legume intercropping gives several ecological benefits including increased interception and utilization of photosynthetically active radiation (PAR; Keating & Carberry, 1993) [18]. Complementary canopy architecture in a pea-barley intercropping system enhances light distribution and minimises radiation losses. The general shape of the three crops is erect, with barley being the vertical crop and pea the lower canopy crops, which means that there is efficient vertical stratification of light interception (Hauggaard-Nielsen *et al.*, 2001) [13]. Optimised row configuration has been shown to boost PAR interception and total canopy photosynthesis in wheat-pea and maize-bean intercropping systems over monocropping systems (Zhang *et al.*, 2008; Bedoussac *et al.*, 2015) [5]. Alternate row and strip row layouts are often used for better radiation-use efficiency to promote better canopy aeration and deeper light penetration into lower canopy layers (Brooker *et al.*, 2015) [7]. Wider strip arrangements also limit the excessive shading of legumes by cereals which helps improve the photosynthetic activity and biomass accumulation (Yu *et al.*, 2015) [46]. In intercrops, Leaf Area Index (LAI) and canopy duration are important factors affecting RUE. Cereal-legume systems have been reported to result in a long green canopy and better retention of chlorophyll than sole crops (Lithourgidis *et al.*, 2011) [26]. Physiological benefits result in more dry matter accumulation and yield stability. Utilisation of diffuse and direct radiation is further enhanced by the differences in height, leaf orientation and duration of growth between barley and pea (Keating & Carberry, 1993) [18]. However, narrow rows can also cause increased shading and affect the productivity of legumes, which means they need to be set up correctly (Bedoussac & Justes, 2010) [4]. There are several studies which have measured light interception in cereal-legume cropping systems, but detailed investigations of the PAR dynamics and modelling of cereal-legume systems, specifically into pea-barley intercropping, is limited. The application of spectral imaging, remote sensing and 3D canopy analyses in future research should be combined to find optimal row orientations and plant densities for maximum radiation-use efficiency.

Wider strip arrangements also limit the excessive shading of legumes by cereals which helps improve the photosynthetic activity and biomass accumulation (Yu *et al.*, 2015) [46]. In intercrops, Leaf Area Index (LAI) and canopy duration are important factors affecting RUE. Cereal-legume systems have been reported to result in a long green canopy and better retention of chlorophyll than sole crops (Lithourgidis *et al.*, 2011) [26]. Physiological benefits result in more dry matter accumulation and yield stability. Utilisation of diffuse and direct radiation is further enhanced by the differences in height, leaf orientation and duration of growth between barley and pea (Keating & Carberry, 1993) [18]. However, narrow rows can also cause increased shading and affect the productivity of legumes, which means they need to be set up correctly (Bedoussac & Justes, 2010) [4]. There are several studies which have measured light interception in cereal-legume cropping systems, but detailed

investigations of the PAR dynamics and modelling of cereal-legume systems, specifically into pea-barley intercropping, is limited. The application of spectral imaging, remote sensing and 3D canopy analyses in future research should be combined to find optimal row orientations and plant densities for maximum radiation-use efficiency.

Water Use Efficiency

Water-use efficiency (WUE) is a key measure of sustainability, especially in rain-fed and semi-arid agroecosystems. Intercropping systems typically have a higher WUE than monocropping, due to complementary rooting, greater soil coverage and lower evaporative losses (Mao *et al.*, 2012) ^[29]. Barley uses mostly upper soil moisture in pea-barley system of intercropping while pea can use deeper soil moisture. This root differentiation reduces direct competition and enhances water extraction efficiency (Hauggaard-Nielsen *et al.*, 2001) ^[13]. The increased water productivity and drought resistance when growing cereal-legume intercrop systems have been consistently reported in studies (Lithourgidis *et al.*, 2011) ^[26]. Optimum row configuration to enhance canopy cover and minimise evaporation losses in the soil. Furthermore, the infiltration and water holding capacity are generally improved, and the microclimatic conditions are better, under strip intercropping systems, which help to reduce runoff (Yu *et al.*, 2015) ^[46]. Maize-pea and wheat-legume cropping systems were found to achieve water use efficiency and yield stability when the row ratio was balanced in water limited conditions (Mao *et al.*, 2012) ^[29]. The improved rhizosphere interaction and soil structure also results in increased drought tolerance in intercropping systems. Legume associated microbial activity leads to improved moisture holding capacity, aggregation and increased moisture availability in periods of stress (Jensen *et al.*, 2020) ^[16]. Denser canopy systems further lessen the evaporative demand and moderate soil temperature fluctuations. Row placement has a significant effect on WUE. A high ratio of cereal to legumes can increase competition for water and inhibit legume establishment, while balanced ratios like 2:1 generally result in optimal complementary water-use patterns (Bedoussac *et al.*, 2015) ^[5]. However, this is dependent on the distribution of the rainfall, soil properties and the genotype of the crops. Isotopic tracing, root imaging technology and soil moisture modeling should be used in future studies to gain more knowledge of below-ground water dynamics under climate change in intercropping pea-barley.

Nutrient Use Efficiency

Cereal-legume intercropping systems have several benefits, including Nutrient-Use Efficiency (NUE), which involves biological nitrogen fixation by legumes and high N USE efficiency in cereals when available Soil Nitrogen (SIN) is used. This complementarity increases nutrient uptake, decreases fertilizer consumption and increases sustainability. Pea-barley intercropping systems: Pea supplies symbiotically fixed nitrogen, which decreases the need for synthetic nitrogen fertilizers. Nitrogen transfer from legumes to cereal crops can happen by rhizodeposition, through root exudates, decomposition of legume residues and through microbial interactions (Hauggaard-Nielsen *et al.*, 2008) ^[14]. Intercrops often have a

greater NUE when compared to monocrops, especially under moderate fertilizer application rates (Bedoussac *et al.*, 2015) ^[5]. High nitrogen inputs (fertiliser) lower logical nitrogen fixation and raise cereal dominance, thus decreasing inter-crop complementarity (Lithourgidis *et al.*, 2011) ^[26]. Row arrangement strongly impacts nutrient competition and facilitation. Alternate-row systems can increase root interaction and nutrient sharing, compared to strip systems, which can lead to a greater interspecific competition for phosphorus and potassium (Brooker *et al.*, 2015) ^[7]. Root differences between cereals and legumes enhance nutrient exploration from different soil horizons and the efficiency of nutrient recovery. Intercropping systems also help to build up soil microbial biomass, enzyme activity and Soil Organic Carbon (SOC) (Jensen *et al.*, 2020) ^[16]. Root exudates of legumes may help to mobilise P and enhance nutrient availability to the companion cereal crop. A number of studies have also found that the use of fertilizer has been reduced in cereal-legume systems than in cereal-legume-fertilizer systems, and that the combination of legumes and cereal crops is more efficient in nutrient use than either cereal cropping or fertilizer use alone (Bedoussac *et al.*, 2015) ^[5]. Although there is a body of research indicating the nutrient complementarity in intercropping systems, few studies have actually measured the transfer of nitrogen and rhizosphere interaction in pea-barley intercropping systems. The use of isotopic techniques and microbiome analysis in future research would help to better understand nutrient dynamics with different row arrangements.

Energy Use Efficiency

As input costs are increasing and environmental concerns are growing, the energy-use efficiency in sustainable agriculture has become more and more important. Most of the time, intercropping systems are more energy efficient and yield better output-input energy ratios than monocropping systems (Lithourgidis *et al.*, 2011) ^[26]. The use of improved energy efficiency in pea-barley intercropping systems is mainly due to lower nitrogen fertilizer use, efficient use of land and higher biomass production. Pea biological nitrogen fixation greatly reduces reliance on high-energy synthetic nitrogen, resulting in reduced total energy inputs (Jensen *et al.*, 2020) ^[16]. Increase in net energy returns and energy use efficiency have been reported in intercrop of cereal-legume systems when compared to sole crops (Mao *et al.*, 2012) ^[29]. Optimised resource use is an important aspect of a more sustainable production process and a reduced environmental footprint. Intercropping can also help to achieve sustainable intensification by adding value without adding external inputs in the same proportion (Brooker *et al.*, 2015) ^[7]. The energy efficiency is strongly influenced by the row arrangement. Optimized row configurations allow intercultural operations, efficient mechanisation and saving unnecessary investment of labour and inputs. However, intercropping systems with strip configuration can be more efficient in operation than mixed planting systems (Yu *et al.*, 2015) ^[46]. Intercropping systems also help to reduce greenhouse gas emissions, improve carbon sequestration and ecological sustainability (Jensen *et al.*, 2020) ^[16]. The benefits are increasingly being acknowledged as important markers of climate resilient agriculture. But, there are limited studies on the energy budget and life-cycle

assessment specifically with pea-barley intercropping. Future research should include options for carbon accounting, energy auditing, and sustainability assessment tools to assess the long-term environmental impacts of various row configurations.

Constraints, Limitations, and Research Gaps

While the agronomic and ecological benefits of intercropping pea-barley systems are many, several limitations remain in practice, technique and research that hinder the use of such systems on a large scale. One of the major constraints is mechanization difficulty. Intercropping is sometimes carried out between crops with different plant architecture, maturity periods and harvesting methods and this makes sowing and intercultural operations and mechanical harvesting challenging under conventional farming practices. Various row spacing and crop height configurations often complicate efficient use of seed drills, sprayers and combine harvesters, thereby adding to the labour needs for effective operation. There are still significant challenges in harvesting and post-harvest separation of mixed grain, especially if the crops grow asynchronously or have varying moisture, size, and shape of their seeds. Inter-specific competition is also unstable under stress conditions, another important limitation. Climatic factors, soil fertility, and water availability are key factors in determining the balance between facilitation and competition in cereal-legume intercrops. Drought, heat stress and/or nutrient deficient conditions may make cereals like barley too competitive and inhibit pea growth, leading to reduced intercrop productivity and stability. There is also genotypic variability in the compatibility of intercrops and environmental diversity, which make optimization of intercrop performance in various agroecological regions even more complex. The knowledge about row arrangement and spatial configuration is still limited. The studies have concentrated on a few row ratios (1:1 and 2:1 arrangements under shortterm experimental conditions) while wider evaluations of the effects of strip width optimization, paired row systems and variable plant densities have not been widely studied. Moreover, many experiments are performed under controlled or site-specific conditions which do not allow conclusions to be extended to different climatic zones and production systems. The long-term studies on soil fertility dynamics, soil carbon sequestration, weed ecology and system resilience are still inadequate in pea-barley intercropping systems. Precision agriculture and climate-smart intercropping are among the other major research gaps. Agricultural technologies for precision agriculture are rapidly developing and are being adopted in modern agriculture; however, when it comes to intercropping systems, very little has been done. Most precision farming tools are developed for a monocrop system and are not optimized for intercrop canopies and spatial arrangement. In addition, there is a lack of information on the ability of intercrops to respond to climate variability, increased temperature, unpredictable rainfall and extreme climatic events. Further investigations concerning the development of mechanization-compatible row arrangements, designs based on climate-resilient intercrops, precision nutrient and water management and long-term experiments involving multidisciplinary studies should be a priority. The combination of remote sensing, root phenotyping, crop models and artificial intelligence could significantly

enhance our knowledge and optimization of intercropping systems of pea-barley under future climate scenarios.

Conclusion

The intercropping of pea and barley is an efficient and sustainable cropping system that is more productive, efficient in the use of resources, and more ecologically stable than monocultural systems. The review points out that the arrangement of rows plays an important role in yield, land use efficiency, interception of radiation, water and nutrient use efficiency and overall system efficiency. The balanced spatial arrangements, that is, 1:1 alternate rows and strip intercropping, mostly yield better productivity due to better complementarity between pea and barley and lower interspecific competition. The complementary rooting system, canopy structure and nitrogen fixing capability of pea allows for better resource utilization and increased reliance on internal resources. Intercropping also improves the water use efficiency, soil fertility and sustainability of agriculture, which are appropriate for the climate condition of the region. Some of the obstacles are mechanization problems, variable crop competition in stressful situations and the lack of long-term studies, but these are not limiting its wider use. Future investigations should aim at optimizing row designs for different agroecological zones, establish designs compatible with mechanization, and integrate precision agriculture technologies, crop models and climate-smart management strategies. In general, optimized pea-barley intercropping systems offer high potential to promote sustainable intensification, resource conservation and adaptation to climate change in agriculture.

Authors Contribution

SR designed the idea of manuscript MN collected the papers related to manuscript and SP formatted and edited the manuscript.

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Conflict of Interest

All authors agree to publish the manuscript and there is no conflict of interest.

References

1. Kaur A, Sharma S. Intercropping a sustainable holistic approach for improving growth and productivity of crops. International Journal of Research in Agronomy. 2025. DOI: 10.33545/2618060x.2025.v8.i4b.2757.
2. Akchaya K, Parasuraman P, Pandian K, Vijayakumar S, Thirukumaran K, Roshan M, et al. Boosting resource use efficiency, soil fertility, food security, ecosystem services, and climate resilience with legume intercropping: a review. Frontiers in Sustainable Food Systems. 2025. DOI: 10.3389/fsufs.2025.1527256.
3. Ali F, Moinuddin, Khan FA. Effects of Intercropping on Plant Growth and Yield Performance of Toria (*Brassica campestris* L.) and Field Pea (*Pisum sativum* L.) under Irrigated Conditions. Agricultural Science Digest - a Research Journal. 2022. DOI: 10.18805/ag.d-5493.

4. Bedoussac L, Justes E. Dynamic analysis of competition and complementarity for light and nitrogen in intercrops. *Field Crops Research*. 2010;119:449-466.
5. Bedoussac L, Journet EP, Hauggaard-Nielsen H, Naudin C, Corre-Hellou G, Jensen ES, et al. Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops. *Field Crops Research*. 2015;183:94-107.
6. Brahimi S, Toumatia O, Drevon J, Zitouni A, Lazali M. Intercropping legumes and cereals increases resource use efficiency and crop productivity in low phosphorus soils under semi-arid Mediterranean conditions. *Agroecology and Sustainable Food Systems*. 2022;46:1482-1501. DOI: 10.1080/21683565.2022.2121951.
7. Brooker RW, Bennett AE, Cong WF, Daniell TJ, George TS, Hallett PD, et al. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. *New Phytologist*. 2015;206:107-117.
8. Datta A, Sankaranarayanan S, Bhatia U. Temporally staggered cropping co-benefits beneficial insects and pest control globally. 2025.
9. Demie D, Döring T, Finckh M, Van Der Werf W, Enjalbert J, Seidel S. Mixture × Genotype Effects in Cereal/Legume Intercropping. *Frontiers in Plant Science*. 2022;13. DOI: 10.3389/fpls.2022.846720.
10. Feng L, Yang W, Tang H, Huang G, Wang S. Bandwidth Row Ratio Configuration Affect Interspecific Effects and Land Productivity in Maize-Soybean Intercropping System. *Agronomy*. 2022. doi: 10.3390/agronomy12123095.
11. Gu CX, et al. Weed-suppressive ability and species dominance in intercropping: A meta-regression. *Journal of Ecology*. 2025;113:2234-2247. DOI: 10.1111/1365-2745.70090.
12. Gungaabayar A, Jha A, Warkentin T, Knight J, Penner G, Biligetu B. Forage yield and biological nitrogen fixation of pea-cereal intercrops for hay production. *Agronomy Journal*. 2022. DOI: 10.1002/agj2.21270.
13. Hauggaard-Nielsen H, Ambus P, Jensen ES. Interspecific competition, N use and interference with weeds in pea-barley intercropping. *Field Crops Research*. 2001;70:101-109.
14. Hauggaard-Nielsen H, Jørnsgaard B, Kinane J, Jensen ES. Grain legume-cereal intercropping: The practical application of diversity, competition and facilitation in arable systems. *Renewable Agriculture and Food Systems*. 2008;23:3-12.
15. Jaskulska I, et al. Peas and Barley Grown in the Strip-Till One Pass Technology as Row Intercropping Components in Sustainable Crop Production. *Agriculture*. 2022. DOI: 10.3390/agriculture12020229.
16. Jensen ES, Carlsson G, Hauggaard-Nielsen H. Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N. *Agronomy for Sustainable Development*. 2020;40:1-15.
17. Jin F, et al. Quantification of spatial-temporal light interception of crops in different configurations of soybean-maize strip intercropping. *Frontiers in Plant Science*. 2024;15. DOI: 10.3389/fpls.2024.1376687.
18. Keating BA, Carberry PS. Resource capture and use in intercropping systems. *Field Crops Research*. 1993;34:273-301.
19. Kou H, et al. Grain yield, water-land productivity and economic profit responses to row configuration in maize-soybean strip intercropping systems under drip fertigation in arid northwest China. *Agricultural Water Management*. 2024. DOI: 10.1016/j.agwat.2024.108817.
20. Kou H, et al. Light Distribution, Interception and Use Efficiency of Drip-Fertigated Maize-Soybean Strip Intercropping Systems Under Various Row Configuration Conditions. *Plant, Cell & Environment*. 2025. DOI: 10.1111/pce.70031.
21. Lai H, Gao F, Su H, Zheng P, Li Y, Yao H. Nitrogen Distribution and Soil Microbial Community Characteristics in a Legume-Cereal Intercropping System: A Review. *Agronomy*. 2022. DOI: 10.3390/agronomy12081900.
22. Landschoot S, Zustovi R, Dewitte K, Randall N, Maenhout S, Haesaert G. Cereal-legume intercropping: a smart review using topic modelling. *Frontiers in Plant Science*. 2024;14. DOI: 10.3389/fpls.2023.1228850.
23. Lebreton P, Bedoussac L, Bonnet C, Journet E, Justes E, Colbach N. Optimal species proportions, traits and sowing patterns for agroecological weed management in legume-cereal intercrops. *European Journal of Agronomy*. 2024. DOI: 10.1016/j.eja.2024.127266.
24. Li C, Stomph T, Makowski D, Li H, Zhang C, Zhang F, et al. The productive performance of intercropping. *Proceedings of the National Academy of Sciences of the United States of America*. 2023;120. DOI: 10.1073/pnas.2201886120.
25. Li G, et al. Enhancing production efficiency through optimizing plant density in maize-soybean strip intercropping. *Frontiers in Plant Science*. 2024;15. DOI: 10.3389/fpls.2024.1473786.
26. Lithourgidis AS, Dordas CA, Damalas CA, Vlachostergios DN. Annual intercrops: an alternative pathway for sustainable agriculture. *Australian Journal of Crop Science*. 2011;5:396-410.
27. Lu JL, et al. Row ratio increasing improved light distribution, photosynthetic characteristics, and yield of peanut in the maize and peanut strip intercropping system. *Frontiers in Plant Science*. 2023;14. DOI: 10.3389/fpls.2023.1135580.
28. MacLaren C, Waswa W, Aliyu K, Claessens L, Mead A, Schöb C, et al. Predicting intercrop competition, facilitation, and productivity from simple functional traits. *Field Crops Research*. 2023. DOI: 10.1016/j.fcr.2023.108926.
29. Mao L, Zhang L, Li W, van der Werf W, Sun J, Spiertz H, et al. Yield advantage and water saving in maize/pea intercrop. *Field Crops Research*. 2012;138:11-20.
30. Martin-Guay MO, Paquette A, Dupras J, Rivest D. The new Green Revolution: sustainable intensification of agriculture by intercropping. *Science of the Total Environment*. 2018;615:767-772.
31. Mbanyele V, Enesi R, Shaw L, Gorim L. A review of intercropping systems in Western Canada. *Agronomy Journal*. 2024. DOI: 10.1002/agj2.21622.
32. Neelam N, Dhaka A, Satpal S, Shweta S, Devi U, Hooda V. Inclusion of legume and oilseed crop in barley-based intercropping system for enhancing land utilization and productivity. *Agriculture Association of Textile Chemical and Critical Reviews*. 2025. DOI: 10.21276/aatccreview.2025.13.03.133.

33. Neugschwandtner R, Herz P, Böck A, Wagentristsl H, Moitzi G, Klimek-Kopyra A, et al. Crop Growth Analysis of Autumn- and Spring-Sown Wheat-Pea Intercrops. *Agronomy*. 2025. DOI: 10.3390/agronomy15020477.
34. Nurgi N, Tana T, Dechassa N, Tesso B, Alemayehu Y. Effect of spatial arrangement of faba bean variety intercropping with maize on yield and yield components of the crops. *Heliyon*. 2023;9. DOI: 10.1016/j.heliyon.2023.e16751.
35. Pampana S, Arduini I, Andreuccetti V, Mariotti M. Fine-Tuning N Fertilization for Forage and Grain Production of Barley-Field Bean Intercropping in Mediterranean Environments. *Agronomy*. 2022. DOI: 10.3390/agronomy12020418.
36. Rahman K, Saati-Santamaría Z, García-Fraile P. Intercropping of non-leguminous crops improves soil biochemistry and crop productivity: a meta-analysis. *The New Phytologist*. 2025. DOI: 10.1111/nph.70037.
37. Raza M, et al. Maize/soybean strip intercropping produces higher crop yields and saves water under semi-arid conditions. *Frontiers in Plant Science*. 2022;13. DOI: 10.3389/fpls.2022.1006720.
38. Raza MA, et al. Spatial differences influence nitrogen uptake, grain yield, and land-use advantage of wheat/soybean relay intercropping systems. *Scientific Reports*. 2023;13. DOI: 10.1038/s41598-023-43288-3.
39. Ruillé M, Beillouin D, Prudhomme R. Ecological drivers of intercropping performance for enhanced global crop production. *npj Sustainable Agriculture*. 2026;4. DOI: 10.1038/s44264-025-00110-z.
40. Salinas-Roco S, Morales-González A, Espinoza S, Pérez-Díaz R, Carrasco B, Del Pozo A, et al. N₂ Fixation, N Transfer, and Land Equivalent Ratio (LER) in Grain Legume-Wheat Intercropping: Impact of N Supply and Plant Density. *Plants*. 2024;13. DOI: 10.3390/plants13070991.
41. Shao Z, Hu S, Fan C, Meng Z, Yan X, Ji W, et al. Optimizing Row Ratio Configurations for Enhanced Productivity and Resource-Use Efficiency in Maize-Alfalfa Intercropping. *Plants*. 2025;14. DOI: 10.3390/plants14243846.
42. Thinley K, et al. Establishment of a high-yield intercropping system for maize and legumes under rainfed conditions in eastern Bhutan. *Plant Production Science*. 2024;27:170-184. DOI: 10.1080/1343943x.2024.2354544.
43. Toker P, Canci H, Turhan I, Isci A, Scherzinger M, Kordrostami M, et al. The advantages of intercropping to improve productivity in food and forage production - a review. *Plant Production Science*. 2024;27:155-169. DOI: 10.1080/1343943x.2024.2372878.
44. Vezy R, Munz S, Gaudio N, Launay M, Lecharpentier P, Ripoché D, et al. Modeling soil-plant functioning of intercrops using comprehensive and generic formalisms implemented in the STICS model. *Agronomy for Sustainable Development*. 2023;43:1-18. DOI: 10.1007/s13593-023-00917-5.
45. Wu J, Bao X, Zhang J, Lu B, Zhang W, Callaway R, et al. Temporal stability of productivity is associated with complementarity and competitive intensities in intercropping. *Ecological Applications: a publication of the Ecological Society of America*. 2022;e2731. DOI: 10.1002/eap.2731.
46. Yu Y, Stomph TJ, Makowski D, van der Werf W. A meta-analysis of relative crop yields in cereal/legume mixtures suggests options for management. *Field Crops Research*. 2015;198:269-279.
47. Zhao J, Chen J, Beillouin D, Lambers H, Yang Y, Smith P, et al. Global systematic review with meta-analysis reveals yield advantage of legume-based rotations and its drivers. *Nature Communications*. 2022;13. DOI: 10.1038/s41467-022-32464-0.
48. Zheng H, et al. Effects of Row Spacing and Planting Pattern on Photosynthesis, Chlorophyll Fluorescence, and Related Enzyme Activities of Maize Ear Leaf in Maize-Soybean Intercropping. *Agronomy*. 2022. DOI: 10.3390/agronomy12102503.
49. Zhu S, Zhu H, Zhou R, Zhang W, Wang W, Zhou Y, et al. Intercrop overyielding weakened by high inputs: Global meta-analysis with experimental validation. *Agriculture, Ecosystems & Environment*. 2023. DOI: 10.1016/j.agee.2022.108239.
50. Anchal A, Kaur AA, Sharma S. Intercropping a sustainable holistic approach for improving growth and productivity of crops. *International Journal of Research in Agronomy*. 2025;8(4):133-9.