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Row configuration strategies in pulse cereal intercropping systems: A review on chickpea barley combinations

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Abstract

Intercropping of pulses and cereals is one of the most important practices of sustainable agriculture as it benefits in improving the productivity and efficiency in resource use, coupled with ecological stability, especially in rain-fed and marginal agriculture. Chickpea-barley intercropping has received significant attention compared to other pulse-cereal combinations because of its complementary nature, nutrient use efficiency, and utilization of water, light, and space, as well as the mitigation of production risks under changing climate conditions. This review critically investigates various row configuration approaches used in chickpea-barley intercropping systems and the effect on growth, yield, and performance indices, nutrient dynamics, weed suppression, and profitability. The results suggest that the row arrangements of 2:1, 3:1, and paired-row have a significantly higher land equivalent ratio (LER), crop equivalent yield, water-use efficiency, and profitability than monocropping systems. With the presence of chickpea, biological nitrogen fixation and improvement of soil fertility are achieved, whereas good ground cover and resource capture are maintained, and the system is more productive and sustainable with the presence of barley. The proper row orientation and row spacing also help to reduce interspecific competition and enhance microclimatic conditions for both component crops. The review also underscores the importance of intercropping as a strategy for climate-resilient agriculture, citing benefits such as biodiversity, lower reliance on inputs, and soil health benefits. Future research should focus on precision-based management of rows, varietal compatibility, mechanization, and integrated nutrient and water management methods for optimizing the potential of intercropping chickpea with barley under various agro-ecological conditions.

Keywords: Chickpea-barley intercropping, row configuration, land equivalent ratio, resource-use efficiency, sustainable agriculture

1. Introduction

Intercropping has been promoted as an integral approach of sustainable agriculture (Maitra *et al.*, 2021; Akchaya *et al.*, 2025) ^[22, 1], especially under degraded soil and ecosystem conditions in intensive, high-input production systems. Intercropping can improve the yield, stability, and environmental performance by spreading the species over time and space, and uses relatively small amounts of external inputs (Maitra *et al.*, 2021; Sisodia *et al.*, 2025) ^[22, 35]. Combining legumes with cereals is particularly significant as it brings the productivity and natural nitrogen input (Akchaya *et al.*, 2025; Lai *et al.*, 2022) ^[1, 19] along with the soil health improvement.

Intercropping offers various advantages in sustainable production systems, including enhanced land value, resilience of the production system, pest, disease, and weed control, and better use of light, water, and nutrients (Maitra *et al.*, 2021; Homulle *et al.*, 2021; Lai *et al.*, 2022) ^[22, 14, 19]. Legumes, which are used in mixtures, can also fix N₂ in the air, reduce the need to use synthetic N fertilizers in the soil, improve soil organic matter, help loosen hardpans and prevent soil erosion - all of which contribute to long-term soil fertility and to lowering environmental footprints (Maitra *et al.*, 2021; Akchaya *et al.*, 2025; Lai *et al.*, 2022) ^[22, 1, 19]. Intercrops of cereals with legumes yield a superior yield advantage and land equivalent ratio of >1.0, and water and nutrient use efficiency, and lower yield losses due to biotic stresses (Akchaya *et al.*, 2025; Demie *et al.*, 2022; Mbanyele *et al.*, 2024) ^[1, 6, 25].

The direct contribution of pulse-cereal systems for food and nutrition security also cannot be ignored. Legumes act as a protein supplement to cereals and can be grown on the same land area to produce energy and protein-rich grain and forage to provide more balanced diets, and to maintain or enhance the total caloric and protein production per unit land area (Akchaya *et al.*, 2025; Sisodia *et al.*, 2025; Książak *et al.*, 2023) ^[1, 35, 17]. They help to make the systems more resilient to the variable climate conditions, enhance water holding capacity, and sustain biodiversity and microbial activity that determines nutrient cycling (Akchaya *et al.*, 2025; Sisodia *et al.*, 2025; Lai *et al.*, 2022) ^[1, 35, 19].

In general, intercropping of chickpea-barley is a strategic pulse-cereal intercropping system. In the pea-barley system, and other grain legume-cereal systems, it was found that cereals grown in combination with pulses have improved grain and forage quality, with higher nodulation and biological N fixation in the legume, and higher N recovery, than cereals grown alone (Mbanyele *et al.*, 2024; Akchaya *et al.*, 2025) ^[25, 1]. The combination of intercropping of chickpea and barley holds special potential for low-input agricultural systems that aim for high productivity, good soil health, and dietary protein provision in the same system.

2. Concept and Principles of Intercropping

Intercropping refers to the cultivation of two or more crops simultaneously in the same field, such that the two crops are present in the same field for a considerable amount of the crop's growing season. It is also referred to as polyculture or mixed cropping, and it seeks to increase overall production, better use of resources, and also to increase ecological stability over sole crops (Maitra *et al.*, 2021; Ebbisa, 2022) ^[22, 9]. Generally, intercropping involves growing two or more crops (one main crop and one or more secondary crops) with the main crop as the primary economic crop (Maitra *et al.* 2021) ^[22].

The classification of intercropping is primarily according to the spatial and temporal structures. Intercropping can be done in a variety of different ways, including relay intercropping (releasing a second crop into the mid-growth stage of a standing main crop), strip intercropping (two or more crops sown in adjacent strips wide enough for separate attention, but narrow enough to interact), and mixed intercropping (two or more crops sown at the same time without any single row pattern) or intercropping in rows (crops planted in separate rows, with regular row patterns) (Burgess *et al.*, 2022; Ebbisa, 2022) ^[5, 9]. These patterns enable spatial and temporal "intensification" of cropping of the same space (Maitra *et al.*, 2021; Ebbisa, 2022) ^[22, 9].

One type of intercropping that is often adopted is the pulse-cereal association (legume-cereal). Legumes can biologically fix atmospheric nitrogen and can supply some of this to the associated cereal, which can decrease fertilizer use and increase soil fertility and soil structure (Maitra *et al.*, 2021; Toker *et al.*, 2024) ^[22, 36]. The LEQ is usually greater than 1, leading to greater combined yield per unit land than if the same crops were grown separately (Toker *et al.*, 2024) ^[36]. They also have the ability to improve nutrient cycling (N, P, K, C), maintain microbial functionality, and boost micronutrient and protein supply to human diets (Sisodia *et al.*, 2025; Picone *et al.*, 2025; Ebbisa, 2022) ^[35, 30, 9].

Ecological and agronomic principles of diversity, complementarity, competition, and facilitation apply to

intercropping. Different species vary in their morphological and phenological traits, which enable them to share light, water, and nutrients to a greater extent, resist climatic stress, suppress weeds, pests, and diseases, create cooler and more favorable microclimates, and enhance long-term productivity and system resilience (Maitra *et al.*, 2021; Sisodia *et al.*, 2025; Zakir *et al.*, 2023; Ebbisa, 2022) ^[22, 35, 41, 9].

3. Botanical and Agronomic Characteristics of Chickpea and Barley:

Growth habit and phenology of chickpea significantly influence its interactions and complementarity with barley, while barley morphology and physiology strongly influence the interactions and complementarity when intercropped. Like other grain legumes, chickpea also exhibits contrasting phenology and growth habit (e.g., determinate vs. indeterminate, differences in days to flowering and maturity, and in canopy architecture), which can be used to generate temporal and spatial niche differences with cereals (Demie *et al.*, 2022; Arriagada *et al.*, 2022) ^[6, 2]. There is significant genotype variation in drought escape/avoidance, osmotic adjustment, leaf traits, root and nodule function under drought stress, and they are relevant targets for selection as they influence the time and duration of active growth and N fixation, which in turn determine the phenological match of N fixation with a companion cereal (Dutta *et al.*, 2022; Arriagada *et al.*, 2022) ^[7, 1].

In intercropping research, barley as a cereal crop is mainly characterized by phenological traits (growth duration, days to flowering/maturity) and morphological traits like plant height and shoot architecture (Demie *et al.*, 2022) ^[6]. In cereal-legume mixtures, shorter cereal varieties seem to have a better performance in intercropping, and early and late maturing cereals can be beneficial depending on the partner and environment (Demie *et al.*, 2022) ^[6]. These traits determine the ability to capture light, competitiveness, and the timing of water and nutrient uptake and comprise the complementarity.

The potential for complementarity of chickpea and barley can be seen in the wider cereal-legume context: Planting them together will provide temporal niche complementarity because legumes will fix N, and then provide plant residue that will help the succeeding cereal crop use the mineral N at a different time. Morphological contrasts (such as height, canopy shape, and distribution of the root system) and root-trait "ideotypes" (such as plasticity in root depth, fine root density, and nutrient uptake capacity) can increase vertical and temporal resource-use separation, decrease direct resource-use competition, and improve overyielding and resource-use efficiency in crop combinations of cereals and legumes (Homulle *et al.*, 2021; Demie *et al.*, 2022) ^[14, 6].

4. Row Configuration in Intercropping Systems

Row configuration of intercropping involves the pattern of arrangement of crop species in rows, strips, and mixtures, their row space, proportion, and relative position. It is a determinant of the number of plants of the same (conspecific) and different (heterospecific) species that each plant has as neighbours, and therefore of the intensity of the interspecific vs intraspecific interactions (Homulle *et al.*, 2021) ^[14]. Row configuration plays a significant role since it can either improve or deteriorate the performance of intercrop if compared to monocrop in terms of yield,

management, and ecosystem services benefits (Maitra *et al.*, 2021; Akchaya *et al.*, 2025) ^[22, 1]. For instance, row and strip intercropping enhance the availability of machinery and specific fertilization and pest management, while maintaining some species interaction and biodiversity advantages (Homulle *et al.*, 2021; Akchaya *et al.*, 2025) ^[14, 1].

The relative abundance (row ratio) of rows or plants of various species has a significant effect on the competition/complementarity relationship. If the competitive level of the more competitive crop is too high, the system will go towards dominance and “compensation”, meaning that one crop will gain at the expense of another (Maitra *et al.*, 2021) ^[22]. Balancing or intentional asymmetry of ratios can improve the complementarity, arising from partitioning of resources (light, water, nutrients) in time and space for crops, where both are better off than they would be individually, resulting in increased productivity of the mixed stand (Maitra *et al.*, 2021; Homulle *et al.*, 2021) ^[22, 14]. Changing the distance between rows and plants changes belowground competition and the shading effect, which can either increase or decrease belowground competition or promote niche differentiation/facilitation for water and nutrient uptake, respectively (Homulle *et al.*, 2021; Dzvene *et al.*, 2023) ^[14, 8].

Spatial arrangement is, therefore, a key aspect of efficiency in the use of resources. When appropriate geometry is used, intercropping systems are able to better utilize land area, soil moisture, nutrients, sunlight, and CO₂, and they may result in greater biomass and yield due to the reduction of intraspecific competition and the enhancement of intraspecific complementarities (Maitra *et al.*, 2021) ^[22]. Uniform and well-designed patterns facilitate access to light, mitigate weed pressure, and promote good root distribution to help crops access different soil depths and microhabitats to capture more water and nutrients and boost resilience of the system (Maitra *et al.*, 2021; Homulle *et al.*, 2021; Dzvene *et al.*, 2023) ^[22, 14, 8].

5. Different Row Configuration Strategies in Chickpea-Barley Intercropping

The beneficial or detrimental nature of the row configuration in the intercrop of chickpea-barley differs in several ways, primarily because it alters the plant density, identity of neighbours, and light, water, and nutrient availability to the plants. Row geometry and planting pattern thus provide important pointers to push the system towards achieving resource-use complementarity and maximum combined productivity (Akchaya *et al.*, 2025; Maitra *et al.*, 2021) ^[22, 1].

A 1:1 row configuration (alternate rows of chickpea and barley) is a traditional type of row-intercropping, where one

row of chickpea is grown in the same row as barley. This allows for a high number of heterospecific neighbours and fewer conspecific neighbours, thereby supporting interspecific interactions and resource sharing (Landschoot *et al.*, 2024; Mahlayeye *et al.*, 2022) ^[20, 21]. These usually provide greater complementarity regarding light and soil resources than wider strips; however, they are more diverse in management and harvesting and less easily mechanised (Akchaya *et al.*, 2025; Landschoot *et al.*, 2024) ^[1, 20].

In a 2:1 or 3:1 ratio, the two or three rows of the base crop (usually barley) are alternated with one row of chickpea. Replacement-series patterns involve the replacement of some rows of the sole crop with its companion, and in these patterns, total crop population may be as large as or greater than the monoculture, depending on the within-row spacing (Maitra *et al.*, 2021) ^[22]. To maximize yield advantage in barley, the number of rows needs to be increased to boost intraspecific competition, which can also lead to greater barley dominance; yield advantage is dependent on careful management of density to ensure legume still provides N fixation and yield (Maitra *et al.*, 2021; Akchaya *et al.*, 2025) ^[22, 1].

Paired-row systems are two rows of the base crop with a wider intercrop row. It is generally claimed that this geometry results in a larger intercrop space, ensures a base crop density of at least sole crop density, and can boost total yield and monetary returns in additive designs (Maitra *et al.*, 2021; Mbanyele *et al.*, 2024) ^[22, 25]. Strip intercropping is suitable for introducing several rows of a species together, with a sufficient width to be able to use different machinery, but also within a sufficiently narrow strip to allow interactions (Akchaya *et al.*, 2025; Landschoot *et al.*, 2024) ^[1, 20], thus improving the mechanisation of the crop and separating harvesting.

In additive series, the base crop (e.g. barley) retains 100% of their crop population, and the chickpea is cultivated in inter-row or strip space, which generally leads to a higher plant density and may increase the efficiency of land use, while also increasing the competition, resulting in the need to complement the root zone, structure and N dynamics (Maitra *et al.*, 2021; Burgess *et al.*, 2022; Akchaya *et al.*, 2025) ^[22, 5, 1]. In replacement series, rows of some base-crop species are replaced directly by chickpea, thereby decreasing base-crop density, but in some cases total number of plants is not reduced, or even increased, due to increased planting density in replacement rows (Maitra *et al.*, 2021; Akchaya *et al.*, 2025) ^[22, 1]; this may lead to less competition per plant and better combined productivity when row ratios and spacing are appropriate to the species traits.

Table 1: Key Row-Configuration Concepts in Intercropping

Configuration/pattern	Core idea and typical effect	Citations
1:1, 2:1, 3:1 rows	Vary cereal: legume rows; shift competition vs. complementarity; often used as a replacement series.	(Maitra <i>et al.</i> , 2021; Akchaya <i>et al.</i> , 2025) ^[22, 1]
Paired-row, additive vs. replacement	Paired rows create intercrop space; additive keeps full base-crop density, replacement swaps rows between crops.	(Maitra <i>et al.</i> , 2021; Akchaya <i>et al.</i> , 2025) ^[22, 1]

6. Effects of Row Configuration on Growth Parameters

The row configuration involved in intercropping influences the distribution of light, water, and nutrients, which consequently influences important parameters related to

chickpea growth like plant height, branching, leaf area, canopy shape, and root-nodule development. The balance between intra- and interspecific competition and the potential for complementarity among species also varies

depending on the spatial pattern and the density of species, particularly legumes and cereals (Maitra *et al.*, 2021; Homulle *et al.*, 2021) ^[22, 14].

Row geometry-induced shading and neighbor effects have a significant impact on plant height and branching. In legume-cereal crop combinations, higher density of the crop or poor crop row arrangement may affect light availability for the legume, and cause the plants to elongate stems, change internode length, and alter branching patterns in an attempt to intercept more light; this may result in taller stems, but with diminished stem thickness and lodging resistance (Blessing *et al.*, 2022; Lai *et al.*, 2022) ^[3, 19]. In a more open and upright cereal canopy and with sufficient space for the legume, light intensity within the stand is enhanced, and legume architecture is likely to be more balanced, resulting in more even biomass partitioning and reduced etiolation (Lai *et al.*, 2022; Demie *et al.*, 2022) ^[19, 6].

Leaf Area Index (LAI) and canopy architecture are also influenced by row configuration. The total LAI and the canopy heterogeneity of intercropping can be higher than sole cropping, but this is the result of the intercropping pattern, depending on plant density. Using a paired-row or adjusted-spacing design can boost the LAI, enable complementary layering design, enhance radiation interception, and improve efficiency in the system without causing excessive shading on the legume (Maitra *et al.*, 2021; Blessing *et al.*, 2022) ^[22, 3].

Spatial patterns affect belowground processes such as root growth, root overlap, and nodulation. Intercrops need root trait “ideotypes” that focus on deep or stratified roots and lateral spread, and that vary according to plant neighbourhood structure (Homulle *et al.*, 2021) ^[14]. The nodulation and biological nitrogen fixation of legumes can be enhanced by the high competition between legumes and cereal roots, which reduces the mineral N around the legume nodules, while too many and too dense cereals can hurt the number and biomass of legume nodules (Landschoot *et al.*, 2024; Homulle *et al.*, 2021) ^[20, 14]. Therefore, the row configuration is an important lever in chickpea-based intercrop that can be used to reconcile root competition and facilitation and maintain a vigorous root system and nodulation process.

7. Influence on Yield and Yield Attributes

The yield in intercrops of cereal-legume crops like chickpea-barley depends on neighbour interactions and root distribution, which in turn depends on the row

configuration. The configuration of rows in cereal-legume intercrops like chickpea-barley affects neighbour interactions and root distribution and thereby affects grain yield, total (biological) biomass, harvest index, and yield stability. In legume-based systems, well-formulated multi-species mixtures can be more productive and yield more stable results than monocultures, yet results can vary based on the density, spatial configuration, and trait compatibility of species within the mixture (Homulle *et al.*, 2021; Akchaya *et al.*, 2025) ^[14, 1].

Grain yields of intercrop systems (cereal + legume) are frequently reported as higher (land equivalent ratio > 1) than monocrops, due to greater light, water, and nutrient use efficiency and to the biological nitrogen fixation from the legume, which supports the cereal plant (Homulle *et al.*, 2021; Akchaya *et al.*, 2025; Demie *et al.*, 2022; Mbanyele *et al.*, 2024) ^[14, 1, 6, 25]. Increased or decreased grain yield of the cereal/legume may result, however, from the favouring of the cereal partner over the legume partner by row ratios and/or N management, e.g., high N favouring cereals and suppressing legume yield (Mbanyele *et al.*, 2024) ^[25].

The biological yield and harvest index (HI) is a measure of both resource capture and partitioning to grain. Intercropping has the potential to boost total aboveground biomass (biological yield) by exploring the capacity of both belowground and aboveground resources, that is, by increasing rooting depth, root plasticity, and niche differentiation in space and time, compared to sole crops (Homulle *et al.*, 2021; Akchaya *et al.*, 2025) ^[14, 1]. Mixtures may enhance HI and grain production per unit area if they increase total biomass production without affecting the allocation of grain production relative to one component of the mixture. Overly dense or poorly structured mixtures can lead to an increase in vegetative biomass yet decrease the HI of one component due to shading or high below-ground competition (Homulle *et al.*, 2021) ^[14].

As far as the stability of yield is concerned, diversification in space (row/strip patterns) and function (cereal vs. legume) offers some hedge against the variability in the weather, pests, and soil, resulting in more stable biomass and grain production over time (Homulle *et al.*, 2021; Akchaya *et al.*, 2025; Burgess *et al.*, 2022) ^[14, 5]. Root-trait complementarity and plasticity are particularly important for yield stability under stress conditions, and row designs that favour complementarity are likely to improve yield stability across years (Homulle *et al.*, 2021) ^[14].

Table 2: Yield Components in Legume Intercropping Systems

Yield aspect	Typical intercrop effect vs. monocrop	Citations
System grain yield / LER	Often higher, if competition is balanced	(Homulle <i>et al.</i> , 2021; Mbanyele <i>et al.</i> , 2024) ^[14, 25]
Total biomass (biological yield)	Frequently increased by complementarity	(Homulle <i>et al.</i> , 2021; Akchaya <i>et al.</i> , 2025) ^[14, 1]
Yield stability over the years.	Generally improved by diversification	(Homulle <i>et al.</i> , 2021; Akchaya <i>et al.</i> , 2025) ^[14, 1]

8. Resource Use Efficiency in Chickpea-Barley Systems

The resource use efficiency in the chickpea-barley system will rely on the ability of the two species to share light, water, and nutrient resources and the N₂ fixation capacity of chickpea. While the majority of evidence is based on general legume-cereal intercropping, the same principles can be used for intercropping chickpea-barley. By

intercepting more of the radiation over time and space, legging up a legume-based intercropping system usually results in more efficient use of light and photosynthesis than single-cropping systems. Cereals and legumes have different height, leaf angle, and phenology, and when grown together, the grown-up area captures more light with less self-shading compared to sole crops, with higher biomass and yield per

unit land area when the competition among the crops is well managed (Govindasamy *et al.*, 2023) ^[13]. With ~30-35% increase in the main-crop-equivalent yield of legume intercrop, this suggests the system-level photosynthetic efficiency is higher, with better radiation capture being the key to this yield gain observed in legume intercropping (Maitra *et al.*, 2021) ^[22].

Water use efficiency can be improved by legume intercropping through improving soil structure and organic matter, increasing soil water holding capacity, and decreasing soil water evaporation and runoff. The water-use efficiency in various systems also improved by 20-25% in legume intercrops as compared to sole crop, mainly due to deeper or more diversified rooting, better soil cover, and physical properties of the soil (Maitra *et al.*, 2021) ^[22]. These mechanisms enable higher biomass and grain production while using less water. In terms of nutrient-use efficiency and biological nitrogen fixation (BNF), it can be claimed that legumes can be integrated into cereal systems to reduce the amount of N required as a fertilizer or supplement, and increase N cycling. The nutrient use efficiency can be enhanced by 25-30% due to the increased soil organic matter, microbial activity, and P, K, and S accumulation under legume presence, and legumes can fix 80-350 kg N ha⁻¹ season⁻¹, with an average of ~125 kg N ha⁻¹ (Maitra *et al.*, 2021; Govindasamy *et al.*, 2023) ^[22, 13]. In legume-cereal mixtures, the cereals take up soil mineral N (SIN) rapidly reducing N availability to the legume in its rhizosphere and thereby stimulating its nitrogenase activity and BNF, while a part of fixed N is released to the cereal through root residues, exudation, and rhizosphere processes, which increases system-level N use efficiency (SINUE) (Lai *et al.*, 2022; Govindasamy *et al.*, 2023) ^[19, 13].

9. Competition and Compatibility Indices

The two important indices to estimate the performance of intercrop combinations with respect to those of monocrops are competition and compatibility indices. The competition and compatibility indices are two important indices used to estimate the performance of intercrop combinations with respect to monocrop combinations. They can be used to help determine if mixtures use land and resources more efficiently, the degree of competition between crops, and the economic return of intercropping. The most popular criterion used to compare intercrops to monocultures is called Land Equivalent Ratio (LER). It is a measure of the proportion of land area needed for the sole crops for the same amount of yield as an intercrop. LER is computed as a sum of partial LERs, which is the yield of the intercrop divided by the yield of the sole crop (Khanal *et al.*, 2021; Landschoot *et al.*, 2024) ^[16, 20]. For land use advantage, the values of LER are greater than 1, such as LER = 1.15 (Khanal *et al.*, 2021; Maitra *et al.*, 2021) ^[16, 22], which would mean that 15% more land would be required in monoculture to achieve the yield of intercrop. If the LER value is less than 1, then it is a disadvantage. LER can be calculated on the basis of yield of grain, biomass, energy, or value, and it is proposed as a key parameter of the assessment of intercropping (Khanal *et al.*, 2021; Maitra *et al.*, 2021) ^[16, 22].

In addition to LER, there have been several competition and compatibility indices developed. Index values have been described to characterise situations of mutualism (two species benefit from one another), suppression (one species

is inhibited by the presence of another), and mutual inhibition (both species are inhibited in the presence of the other) and to quantify the strength of the mutualism or the balance of the interaction (Maitra *et al.*, 2021) ^[22]. They involve such indicators as aggressivity, competition ratio, and relative crowding coefficient, which are relative yield or relative density measures to determine whether one species is more competitive or if relative yields or densities are relatively even. The economic indices like monetary advantage index extend the LER-like measures by assigning weights to the prices and costs to find out if the biological advantage is reflected in the economic gain; this overcomes one of the major weaknesses of the only biophysical indices (Khanal *et al.*, 2021; Maitra *et al.*, 2021) ^[16, 22]. In general, LER measures the efficiency of land-use, while the indices of aggressivity and monetary indicate who is the winner in the competition and whether it is profitable or not, providing a complete picture of the compatibility of intercropping.

10. Soil Health and Nutrient Dynamics

Legume-cereal crop rotations like chickpea-barley have a significant impact on the health and nutrient cycling in the soil. Main processes are biological nitrogen fixation, soil microbial community changes, and organic matter changes, as well as residual N for subsequent crops. Legumes can enhance soil fertility through the N₂ fixation process and provide N-rich residues to the soil. A wide range of legume intercropping estimated N fixed at 33% higher than conventional practices, an average of 125 kg N ha⁻¹ per season, thus reducing the need for synthetic N fertilizers and increasing soil organic matter, cation exchange capacity, and nutrient availability (Akchaya *et al.*, 2025) ^[1]. Addition of chickpea or legume to cereals has been correlated with high levels of soil organic carbon (up to ~30%), soil structure, lesser bulk density, and water holding capacity, thereby improving soil fertility and resilience (Akchaya *et al.*, 2025) ^[1]. The decomposition of legume residues is relatively fast, resulting in the release of nutrients, such as N, with lower losses than mineral fertilizers, and leads to long-term carbon sequestration and soil quality increases (Zou *et al.*, 2024; Akchaya *et al.*, 2025) ^[43, 1].

Legumes leave behind a “legacy” effect for the intercrop cereal, as well as for the subsequent crop. Legumes can reduce the amount of fertilizer equivalent used by 150-200 kg N ha⁻¹ year⁻¹ and also improve the residual soil N by ~10-20% or more, depending on management of residues and environmental conditions (Zou *et al.*, 2024) ^[43]. A significant portion of legume N is stored belowground over time, the decomposition of legume roots and nodules releases belowground N to contribute to the N use efficiency of cereals and subsequent crops and minimises N leaching risks (Zou *et al.*, 2024; Akchaya *et al.*, 2025) ^[43, 1]. The presence of legumes also affects soil microbial activity and the dynamics of soil organic matter. Microbiological attributes such as microbial biomass N, N, and C cycling enzyme activity, and diversity and connectivity of microbial communities like bacteria and fungi are enhanced in intercropping (Lai *et al.*, 2022; Picone *et al.*, 2025; Akchaya *et al.*, 2025) ^[19, 30, 1]. Legumes and cereals have different types of root exudates, such as amino acids, organic acids, phenolics, which can stimulate beneficial microbes, boost nutrient mineralization, drive cycles of nutrients (N, P and C), and contribute to larger soil pools of micro and deep root zone C and N compared to increased CO₂ losses (Picone *et*

al., 2025; Akchaya *et al.*, 2025) ^[30, 1]. Legume-Cereal systems are dynamic engines of soil biological activity that help to reduce the soil's structure, fertility, and multifunctionality over time.

11. Weed, Pest, and Disease Management

The interactions between species from different crops and the species' coverage of resources in space (row/strip geometry) strongly influence weed, pest, and disease management in mixed cropping systems. Intercropping can help suppress weeds, break pest and disease cycles, and increase natural enemies, decreasing the need for pesticides and herbicides. The advantage of intercropping is that it can efficiently occupy the canopy space and has a tight spatial arrangement, so that the light, water, and soil resources consumed by intercropping plants can be utilized, and the resources available for weeds are reduced. Diversified mixtures and competitive companion crops (DMC) (e.g., buckwheat, legumes, grasses) form dense and fast-growing canopies and high root competition, which significantly suppresses weed density and biomass, particularly under row or strip designs, which allow for the maximum combined cover (Bommarco, 2024; Fernando & Shrestha, 2023) ^[4, 10]. Allelopathic intercrops also provide shade, which helps to control weeds, and give out weed-suppressing chemicals (Scavo & Mauromicale, 2021) ^[33]. Pest and disease reduction is dependent on several mechanisms. Crop diversification involves intercropping,

which eliminates large continuous patches of host plants and disrupts the life cycles of pests and pathogens as they do not have hosts as consistently as when the hosts are in pure stands, reducing pest outbreak risk (Mihrete & Mihretu, 2025; Akchaya *et al.*, 2025; Bommarco, 2024) ^[26, 1, 4]. In combination, the effects of mixed canopies and modified microclimates may result in decreased humidity or different airflow that reduces the spread of disease, and the contrasting susceptibilities of the mixture may also “dilute” host availability, reducing the rate at which epidemics spread (Akchaya *et al.*, 2025; Bommarco, 2024) ^[1, 4]. A large number of intercrops also have an effect as physical or sensory barriers, which stifle the movement of pests and obscure host plant cues (Akchaya *et al.*, 2025; Gardarin *et al.*, 2022; Landschoot *et al.*, 2024) ^[1, 12, 20]. The same designs are highly effective in providing ecological pest management benefits. Diverse intercrops, particularly those incorporating legumes, aromatic plants, flowering buckwheat, cover crops, or predators/parasitoids, provide nectar, pollen, and refuge, which leads to higher abundance and diversity of predators/parasitoids, therefore reducing the dependence on chemicals in biological control (Mihrete & Mihrete, 2025; Akchaya *et al.*, 2025; Zhou *et al.*, 2024; Zou *et al.*, 2024) ^[26, 1, 42, 43]. Legume intercropping can reduce yield losses due to pests and diseases by approximately 20-25% and nematode damage by 40-55%, and also provides other ecosystem services and ecosystem resilience (Akchaya *et al.*, 2025) ^[1].

Table 3: Ecological Functions of Intercropping for Weed and Pest Control

Function	Main ecological effect on pests/weeds	Citations
Dense, mixed canopy & root systems	Outcompete weeds, reduce resources	(Bommarco, 2024; Fernando & Shrestha, 2023) ^[4, 10]
Crop diversity & host dilution	Disrupt pest/disease cycles, fewer outbreaks	(Mihrete & Mihretu, 2025; Akchaya <i>et al.</i> , 2025) ^[26, 1]
Habitat for natural enemies	More predators/parasitoids, less spraying	(Mihrete & Mihretu, 2025; Akchaya <i>et al.</i> , 2025) ^[26, 1]

12. Economic Analysis of Chickpea-Barley Intercropping: Economic analysis of intercropping chickpea and barley crops is based on the difference in the production costs, total income, and overall profitability of intercropping versus monocropping. The available studies are largely on cereal-legume systems in general (and pea-barley or wheat-chickpea in particular); however, they can be used to guide chickpea-barley. From a cost of cultivation viewpoint, reviews give importance to various commonly used intercropping indices, such as LER, which do not consider production costs, and the implicit assumption that equal management and input use in intercropping mixtures and sole crop, respectively, can be misleading ecologically (Khanal *et al.*, 2021) ^[16]. The total variable cost per hectare is found to be slightly more in the intercrops than in the sole crop in empirical trials of cereal-legume systems; however, it needs to be balanced by the increased output and decreased requirement for N fertilizer and pesticides (Khanal *et al.*, 2021; Akchaya *et al.*, 2025) ^[16, 1]. In most cases, when evaluating economic efficiency, legume intercropping has a positive effect on monocrops when considering both gross and net returns due to the yield advantage, improved price-weighted output, and reduced input consumption (Akchaya *et al.*, 2025) ^[1]. The gross income and the net returns in maize-legume and chickpea-maize intercropping systems are reported to be significantly

higher than the sole cropping systems, and the benefit-cost ratio of chickpea-maize intercropping is higher than both maize and legume alone, as per the meta-analyses and case studies (Akchaya *et al.*, 2025) ^[1]. Under low input conditions, gross margins of intercrops were greater than at least one of the sole crops in pea-barley and pea-wheat crops (Akchaya *et al.*, 2025) ^[1]. Value-based and profit-based measures provide the best measure of profitability. Khanal *et al.* suggest using the Land Equivalent Ratio (LER) along with a Value Ratio (VR) and/or a Net Gross Margin / Profit Ratio, where the prices and variable costs are explicitly included, and that an economic advantage of intercropping will be reflected in a value ratio (VR) or a net gross margin/profit ratio > 1 (Khanal *et al.*, 2021) ^[16]. In cereal-legume mixtures, these indicators often indicate that intercrops can yield greater profits, particularly in low-input systems where cost savings on inputs like fertilisers and agrochemicals contribute to the already higher biological yield advantage (Khanal *et al.*, 2021; Akchaya *et al.*, 2025) ^[16, 1].

13. Climate Resilience and Sustainability Aspects

The ability of agriculture to adapt to increased drought, heat waves, and other climate extremes is critical to climate resilience in farming. Climate-smart agriculture (CSA) is increasingly being encouraged by promoting mixed and

diversified systems, such as intercropping, that are able to stabilize production, diversify risk, and minimize environmental impacts. Stress combinations can be more detrimental to crop performance than single stresses, as the physiological and molecular responses to a combination of stress are different and unpredictable from single stress studies (Rivero *et al.*, 2021; Mihheteu & Mihheteu, 2025) ^[31]. Adaptation is constrained by the growing variability of climate, and the cost of adaptation decreases as climate variability increases (reviews), but systems that buffer microclimates (e.g., shade, cooler canopy, improved water holding capacity of the soil) and that make use of complementary root and canopy characteristics are important (Franco-Navarro *et al.*, 2025) ^[11]. Climate resilience in relation to resource use efficiency, water use efficiency, and soil health is highlighted as a benefit of legume intercropping, which in turn contributes to climate variability and climate extremes resilience (Akchaya *et al.*, 2025) ^[1].

Broadening crop diversification and intercropping help to reduce risk and buffer yields. Multiple-cropping is termed as an “insurance” system because having more than one species with different stress tolerances and growth patterns will reduce the chance of complete crop failure during periods of droughts, floods, and/or extreme temperatures; if one crop fails, other crops will be able to utilize freed resources and minimize yield loss (Akchaya *et al.*, 2025) ^[1]. This work cited a meta-analysis suggesting that intercropping’s benefits on yield stability relative to monoculture, which is crucial to resist the production volatility in a variable climate, are significant (Franco-Navarro *et al.*, 2025; Akchaya *et al.*, 2025) ^[11, 1]. They are in line with the objectives of climate-smart agriculture. Intercropping and agroforestry are specifically recognized as CSA practices that impact the productivity, stability, ecosystem services, and climate resilience of farms and landscapes (Franco-Navarro *et al.*, 2025; Akchaya *et al.*, 2025) ^[11, 1]. Diversified intercropping systems can have a positive impact on sustainable, climate-smart food systems by enhancing the efficiency of resource use, keeping production going in extreme events, and contributing to soil carbon and biodiversity.

14. Recent Advances and Research Trends

Research on intercropping technology in recent years has been increasingly involved in the design, conservation, and digitalization of the spatial system and has made more and more systems of mixed crops more manageable and productive. Innovation is progressing from simple mixtures of crops in rows to more complex configurations based on the spatial structure of the crop (such as height, root depth, phenology) and the production equipment. In terms of precision planting and mechanised intercropping, the innovation is moving from row mixtures to more sophisticated designs. Reviews highlight that contemporary precision agriculture technologies, such as GPS-guided machinery, variable-rate technology for input application, drones, and sensor networks, enable new, precision levels of strip planting and plant density, and can facilitate mechanised sowing, weeding, and harvesting even within diverse farming systems (Marinello *et al.*, 2023) ^[23]. Imaging tools such as drone-based multispectral cameras and 3D root architecture modelling are being employed to quantify the below- and aboveground complementarity and

optimise planting patterns, without using large, lengthy, multi-factorial field trials (Toker *et al.*, 2024) ^[36]. This paves the way to the new concept of “precision intercropping”, where the machines would follow specific maps of the species, densities, and strip widths in the field.

To enhance resilience, the introduction of conservation agriculture approaches is being mixed with intercropping. In the context of smallholder farming, minimum tillage, residue management, and cereal-legume intercropping are identified as practices that are some of the most effective ways of adapting to drought, ensuring yield stability and enhancing soil health, particularly in semi-arid farming systems (Kuyah *et al.*, 2021; Mavulula *et al.*, 2026) ^[18, 24]. Legume intercropping is consistently found to improve soil structure, organic matter, water holding capacity, stress resistance, disease resistance, and suppress soil-borne pathogens, while also lowering erosion rates and external N inputs in crops, which aligns with the main principles of conservation agriculture (Akchaya *et al.*, 2025; Maitra *et al.*, 2021; Kuyah *et al.*, 2021) ^[1, 22, 18]. But, adoption is still limited due to a lack of labour, access to equipment, and knowledge (Mavulula *et al.*, 2026; Kuyah *et al.*, 2021) ^[24, 18]. Decision support tools and modelling are gaining increasing ground. Datasets of intercrop mixtures, densities, and spatial patterns are now large enough to supply statistical analyses and crop models and thus allow a virtual test of mixtures, densities, and spatial patterns before their field application (Paut *et al.*, 2024) ^[28]. Meanwhile, precision agriculture-based decision support systems that integrate the use of IoT sensors, artificial intelligence (AI)/machine learning (ML) data analysis, and optimization algorithms/processes are being developed, but the majority of current tools are limited to single-crop and input management decisions instead of complete intercropping system designs (Yousaf *et al.*, 2023; Sharma *et al.*, 2021) ^[40, 34]. In agroecology, reviews highlight that digital DSS can support farmers to select and operate diversified systems, but digital literacy and infrastructure are important challenges, as well as the need for integrating farmers' experiential knowledge (Petraki *et al.*, 2025) ^[29].

15. Challenges and Constraints

Biological interactions and practical aspects create challenges and constraints in intercropping. Competition for limited resources, challenges for mechanised operations and harvesting, and a lack of technical information and guidance for farmers on a local basis are key issues. Competition for any resources that exist when two crops grow together can cause a reduction in the crop's main cash crop if not managed well. After their establishment, service or companion crops share the light, water, and nutrients with the cash crop, and this competition can lead to stress and a reduction in the yield of the cash crop, particularly when water or nutrient availability is low (Gardarin *et al.*, 2022) ^[12]. Competition for light is related to relative height, and canopy architecture - tall or fast-growing neighbours can shade the main crop. Higher biomass and a lack of synchronization in soil nitrogen dynamics can cause excessive demand for soil mineral nitrogen by service crops and reduce yields, sometimes creating an undesirable and disease-promoting soil microclimate (Maitra *et al.*, 2021; Gardarin *et al.*, 2022) ^[22, 12].

There is a significant restriction on operation due to mechanization and harvesting. The operation of agro-

technology is difficult because of intercropping, which makes operations more complex than in monoculture operations. Sowing, fertilization, weed control, and especially harvesting are more challenging when crops are of different heights, maturity times, and seed sizes (Maitra *et al.*, 2021; Khanal *et al.*, 2021) [22, 16]. Some of the problems are labor-intensive or destructive harvesting of component crops (at different times), losses to longer duration crops during harvesting of early crops, and mixing of grains, which requires additional separation processes, which increases cost and might affect grain quality and marketability (Maitra *et al.*, 2021; Khanal *et al.*, 2021) [22, 16]. For some systems, the existing combines or headers do not work properly for the intercrop geometry or the sensitive crops traits, which is a constraint to adoption (Khanal *et al.*, 2021) [16].

There is also a significant absence of recommendations in a location-specific manner. Intercropping requires a lot of knowledge and is climate sensitive, relying more on local climate, soil type, crop selection, and seeding configuration (Mbanyele *et al.*, 2024) [25]. For example, factors influencing productivity vary across pedoclimatic conditions, and much of the information available is outdated, dispersed, small plot data, or does not reflect the rotations or machinery used by producers, making it challenging to provide clear and region-specific guidance to producers (Mbanyele *et al.*, 2024) [25].

16. Future Perspectives

A key focus for future research on chickpea/barley intercropping is the development of spatial optimization, close integration with nutrient and water management, and cultivars that are specifically developed for intercropping. Recent reviews on legume intercropping emphasize that the configuration of rows can greatly influence yield, water use efficiency, and economic profit, with the row configuration in maize-soybean drip fertigation systems, for instance, demonstrating a strong effect on the resource use efficiency and profitability of the system (Akchaya *et al.*, 2025) [1]. In general, row, mixed, and strip intercropping follow complementary “toolkits” that should be adopted based on the mechanization requirements, environment, and management objectives, and the effects on light sharing, capture, and harvestability of these crop configurations should be systematically evaluated for chickpea-barley intercropping in the future (Toker *et al.*, 2024) [36].

Another obvious research area is integration with nutrient/water management. The use of legume intercropping is already known to increase the N fixation by 20-25% on average, soil organic matter, and water use efficiency (Akchaya *et al.*, 2025) [1]. The use of sensors, models, and variable rate application for fine-tuning the inputs to intercrop spatial patterns in water-fertilizer coupling technologies, combined with precision fertigation and micro irrigation, is expected to increase the efficiency of resources and reduce losses in future systems (Xing & Wang, 2024; Xing *et al.*, 2024) [38, 39]. Intercropping chickpea-barley in combination with integrated nutrient management (INM) by using balanced mineral fertiliser in combination with organic inputs and biofertilisers has been identified as a promising practice to improve soil health and productivity at the same time (Akchaya *et al.*, 2025; Sande *et al.*, 2024) [1, 32].

On the breeding side, several reviews emphasize that most cultivars are still bred for sole crops; but genotype × cropping system interactions are not uncommon in cereal-legume mixtures, and aspects of crop growth like plant height, phenology, root architecture, and “mixing ability” significantly influence crop performance (Homulle *et al.*, 2021; Demie *et al.*, 2022; Moore *et al.*, 2022; Landschoot *et al.*, 2024) [14, 6, 27, 20]. Future programmes are encouraged to explicitly target intercropping with ideotypes and use genomic prediction, simulation, and “digital breeding” tools to develop combinations of complementary above-ground and below-ground traits, as well as to run virtual tests for potential chickpea-barley combinations before using them in the field (Homulle *et al.*, 2021; Vieira *et al.*, 2025; Jeon *et al.*, 2023) [14, 37, 15].

17. Conclusion

Overall, intercropping of chickpea with barley is a productive and sustainable farming system that can improve land productivity, yield efficiency, soil health, and the profitability of farms under various agroecological conditions. It is noted that the success of pulse-cereal intercropping depends on proper row configuration, which helps in controlling interspecific competition, light interception, nutrient uptake, utilization of moisture, and overall crop compatibility. Balanced row proportions (2:1, 3:1, and paired row planting systems) generally offer better biological efficiency, land equivalent ratio (LER), weed control, and yield stability than sole cropping, among other planting systems. Chickpea provides biological nitrogen fixation and increases the use of environmental resources, while barley provides structure and efficient use of the environment, leading to complementary interactions that increase system sustainability. The right row orientation and spacing further enhance microclimatic conditions and minimize production risks under rain-fed and stress-prone conditions. Further studies are needed on intercropping adapted chickpea and barley cultivars, integration of nutrient and water management in intercrops, precision planting technologies for row crops, mechanization with intercrops, and climate-resilient row configurations. The need for conducting long-term research on soil fertility, carbon sequestration, and economic sustainability will further support the adoption of chickpea-barley intercropping as a resilient and eco-friendly cropping system for sustainable agriculture and food security.

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