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Intercropping for climate-resilient and resource-efficient agriculture: Advances, mechanisms and future prospects

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Abstract

Agricultural production systems are increasingly challenged by declining natural resources, climate variability, and the environmental consequences of intensive monoculture-based farming. Intercropping, the simultaneous cultivation of two or more crops on the same piece of land during a significant part of their growth cycle, has emerged as a sustainable approach for enhancing productivity while maintaining ecological balance. This review synthesizes recent advances in intercropping research with emphasis on its role in improving resource-use efficiency, soil health, biodiversity conservation, and climate resilience. Evidence from diverse agroecosystems indicates that intercropping enhances land-use efficiency, nutrient acquisition, water-use efficiency, and yield stability through complementary interactions among component crops. Legume-based intercropping systems are particularly beneficial due to their ability to fix atmospheric nitrogen, improve soil fertility, and reduce dependence on synthetic fertilizers. Furthermore, crop diversification in intercropping systems contributes to weed suppression, pest and disease regulation, improved soil biological activity, and enhanced ecosystem services. Despite its numerous advantages, the successful adoption of intercropping requires careful selection of crop combinations and appropriate management practices to minimize interspecific competition and optimize resource utilization. Advances in precision agriculture, mechanization, and climate-smart crop management are expected to further improve the feasibility and effectiveness of intercropping systems. Overall, intercropping represents a promising strategy for achieving sustainable agricultural intensification, improving resilience to environmental stresses, and ensuring long-term food and environmental security.

Keywords: Biodiversity, climate resilience; intercropping; resilient agriculture; sustainable

Introduction

Agriculture remains a cornerstone of economic growth, livelihood security and food production in many developing countries. However, increasing population pressure, rapid urbanisation and industrial expansion have substantially reduced the availability of cultivable land, necessitating the development of production systems that can achieve higher productivity with efficient use of available resources (Erasu *et al.*, 2022) ^[14]. Simultaneously, modern agricultural systems are confronted with challenges arising from climate change, soil degradation, declining biodiversity and increasing dependence on external inputs. These concerns have intensified the search for sustainable production strategies capable of maintaining productivity while conserving natural resources.

Intercropping, defined as the cultivation of two or more crop species simultaneously on the same field during a significant portion of their growth cycle, has gained renewed attention as a sustainable approach to agricultural intensification (Goel *et al.*, 2021; Bamboriya *et al.*, 2022) ^[3, 20]. The practice is among the oldest forms of crop production and has been adopted by farming communities for centuries to enhance productivity, reduce production risks and improve resource utilization. Archaeological evidence indicates that diversified cropping systems were practiced in the Indus Valley Civilization (2600-1900 BC), where farmers cultivated multiple crops to adapt to variable environmental conditions (Petrie and Bates, 2017) ^[48]. Similar cereal-legume associations were reported in ancient Mediterranean agricultural systems, highlighting the long-standing role of crop diversification in sustaining agricultural production (Lithourgidis *et al.*, 2011) ^[34].

Despite the widespread adoption of monoculture systems during the Green Revolution era, intercropping continues to play an important role in global food production, particularly in smallholder farming systems across Asia, Africa and Latin America. It is estimated that intercropping contributes nearly 15–20% of global food production and remains a major component of traditional farming systems in resource-constrained environments (Nyawade *et al.*, 2020) ^[44]. While large-scale commercial agriculture often favors monocropping because of operational simplicity and mechanization compatibility, smallholder farmers continue to adopt intercropping as a strategy to improve food security, diversify farm income and reduce vulnerability to climatic and economic uncertainties (Toker *et al.*, 2024) ^[60].

The scientific basis of intercropping lies in the ecological interactions that occur among component crops. These interactions include resource complementarity, niche differentiation, facilitation and competition, which collectively influence system productivity and stability (Khanal *et al.*, 2021) ^[30]. Crops differing in canopy architecture, rooting pattern, nutrient requirements and growth duration are often able to utilize resources such as light, water, nutrients and space more efficiently than sole crops. Consequently, well-designed intercropping systems frequently produce greater total biomass and economic yield than monocropping systems through improved temporal and spatial resource partitioning (Gulwa *et al.*, 2017; Barbier and Burgess, 2017) ^[4, 21]. Enhanced canopy coverage also improves microclimatic conditions by moderating soil temperature, reducing soil evaporation and improving soil moisture conservation (Weißhuhn *et al.*, 2017) ^[63]. Furthermore, crops with contrasting root distributions can exploit nutrients and water from different soil layers, thereby reducing interspecific competition and increasing overall resource-use efficiency (Gebru, 2015) ^[17]. The importance of intercropping has increased considerably in the context of sustainable agriculture and climate-resilient production systems. Numerous studies have demonstrated that intercropping improves land-use efficiency, stabilizes yields, enhances nutrient cycling and reduces dependence on external inputs such as synthetic fertilizers and pesticides (Stomph *et al.*, 2020) ^[57]. Legume-based intercropping systems are particularly valuable because of their capacity to fix atmospheric nitrogen, improve soil fertility and enhance nutrient availability to companion crops (Dwivedi *et al.*, 2015) ^[13]. Increased crop diversity in intercropping systems also contributes to biological regulation of weeds, insect pests and diseases while supporting beneficial organisms and ecosystem services. These benefits ultimately improve productivity, profitability and environmental sustainability (Misra and Ghosh, 2024) ^[43].

Growing concerns regarding climate change have further strengthened interest in intercropping systems. The diversification of crop species reduces production risks by improving system resilience to drought, heat stress and other climatic extremes. Compared with monocultures, diversified cropping systems often exhibit greater yield stability under adverse environmental conditions because component crops differ in their responses to stress and resource availability (Maitra *et al.*, 2023) ^[37]. In contrast, intensive monoculture systems, although highly productive, have contributed to ecological degradation, biodiversity loss, increased pest outbreaks and greater vulnerability to environmental stresses (Singh and Nath, 2020; Crews *et al.*, 2018) ^[10, 54]. Consequently, diversified production systems such as intercropping are increasingly recognized as viable pathways for achieving sustainable

agricultural intensification while maintaining ecosystem integrity (Tensi, 2023) ^[59]. The success of intercropping systems depends on several factors, including crop species selection, planting geometry, sowing proportion, nutrient management and the competitive interactions among component crops (Bamboriya *et al.*, 2022) ^[3]. Appropriate combinations of crops can maximize complementarity and resource sharing, whereas poorly designed systems may intensify competition and reduce productivity. Therefore, understanding the biological, ecological and agronomic mechanisms governing intercropping performance is essential for developing efficient and climate-resilient production systems.

In view of the increasing demand for sustainable agricultural practices, this review critically examines the role of intercropping in enhancing productivity, resource-use efficiency, soil health and climate resilience. Particular emphasis is placed on the ecological mechanisms underlying intercropping advantages, the contribution of intercropping to sustainable agricultural intensification, and future research opportunities for improving the adoption and performance of diversified cropping systems.

Literature search methodology

The present review was prepared by examining a wide range of published literature related to intercropping and its contribution to resource-use efficiency, sustainable agriculture and climate resilience. Relevant information was gathered from well-established scientific databases, including Scopus, Web of Science, Google Scholar, CAB Abstracts and ScienceDirect. Various sources such as peer-reviewed journal articles, review papers, book chapters and technical reports published between 2000 and 2025 were consulted to obtain a broad understanding of the subject. A systematic search was carried out using different combinations of keywords, including “intercropping”, “mixed cropping”, “cereal-legume intercropping”, “resource-use efficiency”, “land equivalent ratio”, “soil health”, “nutrient-use efficiency”, “water-use efficiency”, “climate resilience”, “climate-smart agriculture”, “sustainable intensification”, “crop diversification”, “ecosystem services” and “agricultural sustainability”. In addition to database searches, relevant references cited in selected publications were also examined to identify other useful studies.

The retrieved literature was carefully screened to ensure its relevance to the objectives of this review. Particular attention was given to studies addressing the ecological basis of intercropping, productivity enhancement, efficient use of land, water and nutrients, soil fertility improvement, pest and disease management, biodiversity conservation, climate adaptation and the overall sustainability of cropping systems. Duplicate records and publications lacking adequate scientific information were excluded. While recent studies published between 2015 and 2025 received greater emphasis to capture current developments, earlier landmark studies were also included because of their importance in establishing key concepts and evaluation methods in intercropping research.

After selection, the literature was reviewed and organised into major thematic areas such as concepts and types of intercropping, crop interactions, resource-use efficiency, soil health, ecosystem services, climate resilience, productivity benefits, economic advantages and existing challenges. Bringing together findings from different agroecological regions and cropping systems helped provide a balanced and comprehensive understanding of how intercropping can support more resilient, productive and sustainable agricultural systems.

Indices for evaluating intercropping performance and resource-use efficiency

Several indices have been developed to quantify the performance and competitive interactions of crops in intercropping systems. Among these, the Land Equivalent Ratio (LER), Area Time Equivalent Ratio (ATER), Aggressivity, Competitive Ratio (CR), and Relative Crowding Coefficient (RCC) are widely used (Maitra *et al.*, 2021) [35].

The Land Equivalent Ratio (LER), proposed by Willey and Osiru (1972) [65], is the most commonly used index for evaluating land-use efficiency in intercropping systems. It expresses the relative land area required under sole cropping to produce the same yield obtained in intercropping and is calculated as:

$$LER = \frac{Y_{ab}}{Y_{aa}} + \frac{Y_{ba}}{Y_{bb}} = L_a + L_b$$

Where Y_{ab} and Y_{ba} are the yields of crops *a* and *b* under intercropping, while Y_{aa} and Y_{bb} represent their respective yields under sole cropping (Mead and Willey, 1980 [66]; Panda *et al.*, 2021) [42, 47]. The modified formula for additive series intercropping is expressed as:

$$LER = \frac{Y_{ab}}{Y_{aa} \times Z_{ab}} + \frac{Y_{ba}}{Y_{bb} \times Z_{ba}} = L_a + L_b$$

Where Z_{ab} and Z_{ba} denote the sown proportions of crops *a* and *b*, respectively. An LER value greater than one indicates an advantage of intercropping over sole cropping, whereas a value less than one indicates lower efficiency of the intercropping system (Mead and Willey, 1980 [66]; Panda *et al.*, 2021) [42, 47]. However, in additive series, where the main crop is maintained at full population and intercrops are added, LER values may be overestimated due to combined yield contributions (Hunegnaw *et al.*, 2022) [26]. Despite this limitation, LER remains the most widely used and reliable index for assessing the biological efficiency of intercropping systems (Singh *et al.*, 2023) [55]. Since LER does not account for crop duration, Hiebsch (1978) [22] proposed the Area Time Equivalent Ratio (ATER), which incorporates the time factor and provides a more realistic estimate of system efficiency. It is expressed as:

$$ATER = \frac{(RY_a \times t_a) + (RY_b \times t_b)}{T}$$

Where RY is the relative yield of each crop, t is the duration of the component crop, and T is the total duration of the intercropping system. Although ATER provides a more realistic estimate of productivity, it may sometimes underestimate system performance compared to LER (Bhadu *et al.*, 2021) [6].

Aggressivity, introduced by McGilchrist (1965) [41], is used to determine the dominance of one crop over another in an intercropping system and is calculated as:

$$A_{ab} = \frac{Y_{ab}}{Y_{aa} \times Z_{ab}} - \frac{Y_{ba}}{Y_{bb} \times Z_{ba}}$$

A positive value indicates dominance of crop *a*, a negative value indicates dominance of crop *b*, and a zero value indicates equal competitiveness between the component crops.

The Competitive Ratio (CR), proposed by Willey and Rao (1980) [66], measures the relative competitive ability of component crops and is derived from partial LER values:

$$CR_a = \frac{LER_a}{LER_b} \times \frac{Z_{ba}}{Z_{ab}}, CR_b = \frac{LER_b}{LER_a} \times \frac{Z_{ab}}{Z_{ba}}$$

A CR value greater than one indicates that the crop is more competitive, whereas a value less than one indicates weaker competitiveness.

The Relative Crowding Coefficient (RCC), proposed by De Wit (1960) [11], evaluates the yield advantage of intercropping compared to sole cropping and is expressed as:

$$K = K_{ab} \times K_{ba}$$

Where:

$$K_{ab} = \frac{Y_{ab}}{Y_{aa} - Y_{ab}}, K_{ba} = \frac{Y_{ba}}{Y_{bb} - Y_{ba}}$$

A value of $K > 1$ indicates yield advantage, $K = 1$ indicates no difference between intercropping and sole cropping, and $K < 1$ indicates disadvantage due to interspecific competition.

Table 1: Commonly used indices for evaluating intercropping systems

Index	Purpose	Interpretation	Key Reference
Land Equivalent Ratio (LER)	Measures land-use efficiency	LER > 1 indicates intercropping advantage	Willey and Osiru (1972) [65]; Mead and Willey (1980) [42]
Area Time Equivalent Ratio (ATER)	Evaluates productivity considering crop duration	ATER > 1 indicates superiority	Hiebsch (1978) [22]
Aggressivity	Determines dominance among component crops	Positive value dominant crop	McGilchrist (1965) [41]
Competitive Ratio (CR)	Measures competitive ability of crops	CR > 1 indicates greater competitiveness	Willey and Rao (1980)
Relative Crowding Coefficient (RCC)	Evaluates yield advantage and resource capture	K > 1 indicates yield advantage	De Wit (1960) [11]

Source: Adapted and synthesized from De Wit (1960) [11], McGilchrist (1965) [41], Willey and Osiru (1972), Hiebsch (1978) [22], Mead and Willey (1980) [42], Willey and Rao (1980) [66], Panda *et al.* (2021) [47], Maitra *et al.* (2021) [35] and Singh *et al.* (2023) [55].

Benefits of intercropping

Intercropping is increasingly recognized as a practical and sustainable farming approach that helps farmers produce more while making better use of available resources. By cultivating two or more crops together on the same piece of land, farmers can take advantage of the natural differences between crops, allowing

them to complement one another rather than compete excessively. This approach not only improves productivity but also supports soil health, resource conservation, biodiversity, and farm resilience. Research from different agroecological regions has consistently shown that intercropping can enhance land-use efficiency, nutrient uptake, water-use efficiency, economic

returns, and environmental sustainability while reducing production risks under changing climatic conditions (Maitra *et al.*, 2021; Stomph *et al.*, 2020; Khanal *et al.*, 2021) ^[30, 35, 57].

• **Enhanced productivity and land-use efficiency**

One of the most important advantages of intercropping is its ability to increase overall crop productivity. This improvement occurs because different crops use available resources in complementary ways. In monocropping systems, a single crop occupies a specific ecological niche and relies on a limited range of resources. In contrast, intercropping combines crops with different growth patterns, canopy structures, and rooting systems, enabling more efficient use of sunlight, water, nutrients, and space throughout the growing season (Stomph *et al.*, 2020) ^[57]. Many studies have reported higher yields from cereal-legume intercropping systems compared with sole cropping. For example, Mandal *et al.* (2014) found that maize-based intercropping systems produced higher maize-equivalent yields than sole maize cultivation. Likewise, maize-groundnut and maize-soybean combinations often achieve Land Equivalent Ratio (LER) values greater than one, indicating that the intercrop uses land more efficiently than separate monocultures (Gitari *et al.*, 2018). Global assessments further suggest that intercropping can increase overall productivity by 15-57%, depending on crop combinations, environmental conditions, and management practices (Maitra *et al.*, 2023) ^[37].

• **Improved resource-use efficiency**

The success of intercropping largely stems from its ability to use available resources more efficiently. Different crops often vary in their canopy architecture, growth duration, and rooting depth, allowing them to capture resources from different parts of the environment without directly competing with one another (Khanal *et al.*, 2021) ^[30]. For instance, crops with contrasting canopy structures can intercept sunlight at different levels, improving overall light utilization and photosynthetic activity. Similarly, differences in root distribution enable crops to access water and nutrients from various soil layers, reducing competition and increasing nutrient uptake efficiency (Homulle *et al.*, 2022) ^[25]. As a result, intercropping systems frequently produce greater biomass and make better use of available nutrients than monocropping systems (Stomph *et al.*, 2020) ^[57].

• **Improved water-use efficiency**

Water availability is one of the major factors limiting agricultural production in many parts of the world. Intercropping can help address this challenge by improving the efficiency with which water is captured and utilized. Crops with different rooting depths can extract moisture from different soil layers, reducing competition and maximizing water use within the system (Mao *et al.*, 2012) ^[39]. Research has shown that intercropping systems can achieve 10-20% higher water-use efficiency than sole cropping under water-limited conditions (Nyawade *et al.*, 2020) ^[44]. In addition, better ground cover provided by multiple crops reduces soil evaporation and helps conserve moisture. These advantages are particularly valuable in rainfed and semi-arid regions where water resources are often scarce and unpredictable.

• **Improved soil fertility and nutrient cycling**

Intercropping contributes significantly to maintaining soil fertility and improving nutrient cycling. Legume-based intercropping systems are especially beneficial because legumes can fix atmospheric nitrogen through their symbiotic relationship with rhizobia bacteria. This process increases nitrogen availability in the soil and reduces the need for synthetic nitrogen fertilizers (Dugassa, 2023) ^[12].

Studies have demonstrated improved nutrient uptake and greater nutrient availability in cereal-legume intercropping systems. For example, Książak *et al.* (2023) ^[32] reported higher nitrogen accumulation and improved LER values in wheat-chickpea intercropping compared with sole cropping. Diverse root systems also enhance the uptake of phosphorus and potassium while facilitating nutrient recycling from deeper soil layers (Homulle *et al.*, 2022) ^[25]. Furthermore, increased biomass production and the return of crop residues to the soil contribute to higher soil organic carbon levels and improved long-term soil fertility (Kokkini *et al.*, 2025) ^[31].

• **Enhancement of soil health and ecosystem services**

The benefits of intercropping extend beyond crop yields and nutrient management. Greater plant diversity creates a more favorable environment for soil microorganisms, which play a crucial role in nutrient cycling, organic matter decomposition, and overall soil fertility (Książak *et al.*, 2023) ^[32]. Diverse root systems also improve soil structure by enhancing aggregation, porosity, and water infiltration. In addition, intercropping supports a range of ecosystem services, including nutrient retention, carbon sequestration, biodiversity conservation, and natural regulation of pests and diseases. These ecological benefits strengthen the sustainability of farming systems and reduce dependence on external agricultural inputs (Isbell *et al.*, 2017) ^[28].

• **Weed, pest and disease suppression**

Intercropping can naturally reduce the pressure from weeds, pests, and diseases. The presence of multiple crops creates a more complex environment that limits the growth and spread of unwanted organisms. Dense crop canopies reduce the amount of sunlight reaching the soil surface, making conditions less favorable for weed emergence and growth (Rahaman, 2021) ^[49]. Crop diversity can also interfere with pest movement and disease transmission, making it more difficult for pests and pathogens to establish large populations. Furthermore, intercropping often provides habitats for beneficial insects, pollinators, and natural enemies of pests, enhancing biological control and reducing the need for chemical pesticides. Recent studies have highlighted the role of diversified cropping systems in improving pest management and promoting ecological stability (Kumar *et al.*, 2025) ^[33].

• **Climate resilience and risk reduction**

Agriculture is increasingly affected by climate variability, including droughts, heat waves, and irregular rainfall patterns. Intercropping helps farmers cope with these challenges by spreading risk across different crops. Since component crops often differ in their tolerance to environmental stresses, the failure of one crop may be compensated by the performance of another, resulting in greater overall system stability (Maitra *et al.*, 2023) ^[37].

In rainfed and dryland farming systems, intercropping serves as an effective risk-management strategy by providing more consistent yields and income under uncertain conditions. The diversity within the system enhances adaptability and strengthens resilience to climate-related stresses, making intercropping an important practice within climate-smart agriculture.

• **Economic and livelihood benefits**

Beyond its agronomic and environmental advantages, intercropping can also improve farm profitability and livelihood security. Higher overall productivity, better resource utilization, and lower dependence on external inputs often translate into increased economic returns compared with monocropping systems. In addition, growing multiple crops reduces market-related risks by providing farmers with more than one source of

income. The combined effects of improved productivity, efficient resource use, healthier soils, enhanced biodiversity, and reduced production risks make intercropping a valuable approach for sustainable agricultural development. By supporting both

environmental sustainability and economic stability, intercropping contributes significantly to long-term food security and rural livelihoods (Rehman *et al.*, 2022) [50].

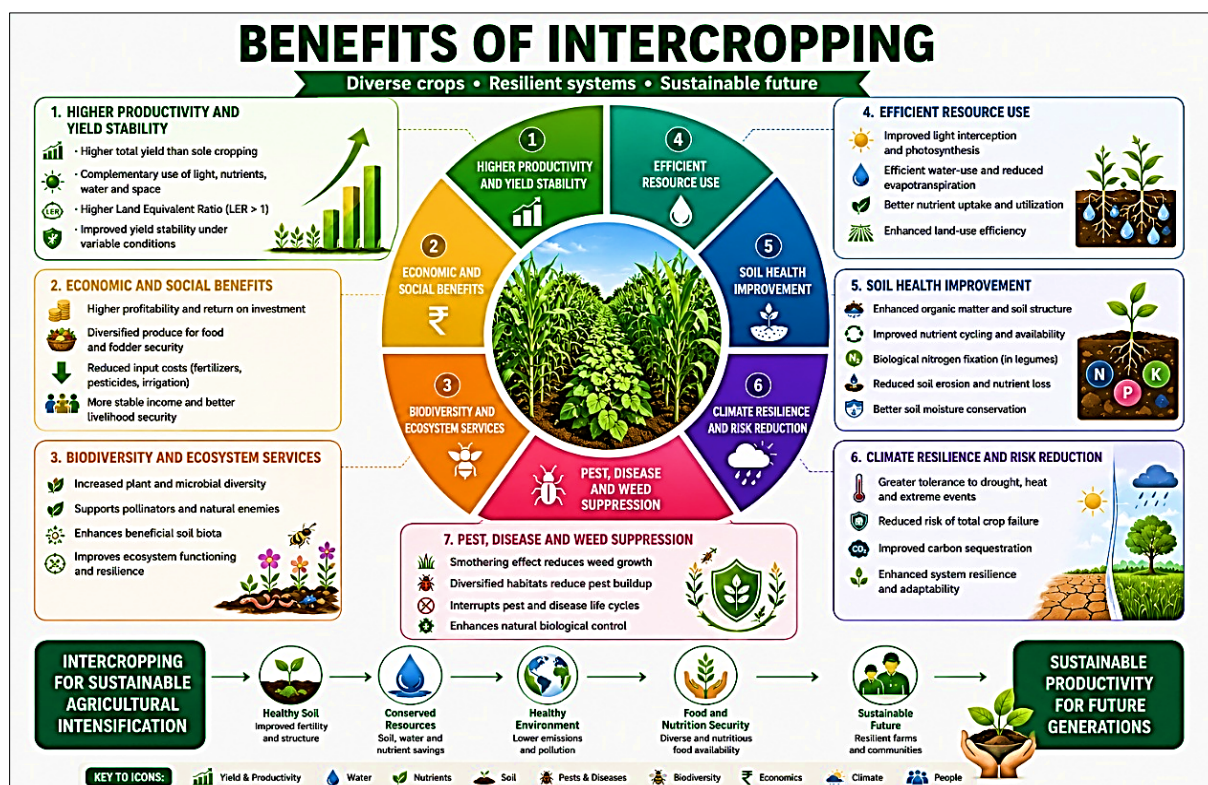


Fig1: Benefits of intercropping (Source: Authors' compilation based on published literature)

Table 2: Quantitative synthesis of intercropping benefits for resilience and resource-use efficiency

System/ Focus	Yield advantage (%)	LER	Nutrient uptake (NPK)	Soil/Resource benefits	Key resilience outcome	Study
Climate-resilient intercropping (review)	10-30% ↑	1.2-1.8	NPK uptake ↑ by 15-25%	Improved SOC, microbial activity	Better drought & heat tolerance	Maitra <i>et al.</i> (2023) [37]
Broadacre systems	15-25% ↑	1.1-1.7	Higher nutrient-use efficiency	Improved water-use efficiency (WUE)	Stable yield in large-scale systems	Khanal <i>et al.</i> (2021) [30]
Mechanistic crop interactions	5-20% ↑	1.1-1.5	Complementarity improves N capture	Efficient light interception	Reduced interspecific competition stress	Stomph <i>et al.</i> (2020) [57]
Agroecological systems	10-25% ↑	>1.0	Improved nutrient cycling	Reduced external input dependency	Long-term sustainability	Wezel <i>et al.</i> (2014) [64]
Potato-legume systems	20-35% ↑	1.3-1.6	N uptake ↑ 20-40%	Reduced erosion, better soil moisture	Enhanced drought resilience	Nyawade <i>et al.</i> (2020) [44]
Legume-based systems	15-30% ↑	1.2-1.7	N ↑ 25-50%, P & K ↑ 10-20%	Improved soil structure	Reduced nutrient losses	Gitari <i>et al.</i> (2019-2021) [19]
Low-input cereal-legume	10-28% ↑	1.2-1.6	N fixation ↑ significantly	Reduced fertilizer requirement	Suitable for low-input farming	Książak <i>et al.</i> (2023)
Food & forage systems	12-30% ↑	1.1-1.8	Balanced NPK uptake	Higher biomass production	Improved system productivity	Toker <i>et al.</i> (2024) [60]
Mixed farming systems	10-20% ↑ income	-	Improved nutrient recycling	Better system diversification	Socio-economic resilience	Homann-Kee Tui <i>et al.</i> (2024)
Legume intercropping	15-35% ↑	1.2-1.7	N fixation ↑ 30-60 kg ha ⁻¹	Enhanced ecosystem services	Reduced GHG emissions	Kokkini <i>et al.</i> (2025) [31]
Industrial systems	5-15% ↑	1.05-1.4	Efficient nutrient capture	Improved biodiversity	Adaptation in mechanized systems	Bybee-Finley & Ryan (2018) [8]
Pest & resilience studies	Variable	-	Improved nutrient balance	Reduced pest incidence	Increased system stability	Huss <i>et al.</i> (2022)
Biodiversity systems	10-25% ↑	-	Enhanced nutrient cycling	Increased ecosystem functioning	Resilience via diversity	Isbell <i>et al.</i> (2017) [28]
Maize-pea system	15-25% ↑	1.2-1.5	Improved N uptake	Water-use efficiency ↑ 10-20%	Drought mitigation	Mao <i>et al.</i> (2012) [39]
Soil nutrient dynamics	-	-	SOC ↑ 10-18%, NPK availability ↑	Improved soil fertility	Long-term sustainability	Singh <i>et al.</i> (2023) [55]

Limitations and challenges of intercropping systems

Despite its numerous agronomic, ecological and economic advantages, intercropping is not without limitations. The successful implementation of intercropping systems depends on careful crop selection, appropriate management practices and favourable environmental conditions. Several biological, agronomic, operational and socioeconomic constraints may reduce the effectiveness of intercropping and limit its large-scale adoption, particularly in highly mechanized agricultural systems.

• Competition among component crops

One of the major challenges associated with intercropping is interspecific competition for essential growth resources such as light, water, nutrients and space. Although intercropping is designed to promote complementary resource utilization, poorly selected crop combinations may intensify competition and reduce the productivity of one or both component crops (Gebu, 2015; Khanal *et al.*, 2021) ^[17, 30]. Competition is particularly severe when component crops possess similar rooting patterns, canopy structures or growth durations, resulting in overlapping resource demands.

The magnitude of competition is influenced by crop species, varietal characteristics, planting geometry, population density and nutrient availability. Therefore, careful selection of compatible crop combinations and optimization of row arrangement, planting ratio and plant population are essential to maximize complementarity and minimize competitive stress (Blessing *et al.*, 2022).

• Allelopathic interactions

Allelopathy represents another important biological constraint in intercropping systems. Certain crop species release secondary metabolites into the surrounding environment that may inhibit seed germination, root growth and overall development of neighboring plants. While some allelopathic effects can contribute to weed suppression, adverse interactions among component crops may negatively affect productivity.

For example, *Juglans nigra* produces juglone, a compound known to suppress the growth of several crop species. Similarly, extracts of *Jatropha curcas* have been reported to inhibit germination and seedling growth in *Capsicum annuum* (Maitra *et al.*, 2021; Islam *et al.*, 2021) ^[35]. Consequently, understanding crop compatibility and allelopathic relationships is essential when designing intercropping systems.

• Complexity of agronomic management

Intercropping systems often require more complex management than monocropping systems because component crops differ in their growth habits, nutrient requirements, irrigation needs and maturity periods. Agronomic operations such as fertilizer application, irrigation scheduling, pest management and harvesting become more challenging when multiple crops are grown simultaneously within the same field (Huss *et al.*, 2022). The requirement for crop-specific management increases labour demand and management skill, making intercropping less attractive in some commercial farming situations. Furthermore, recommendations developed for sole crops may not always be directly applicable to intercropping systems, necessitating site-specific management strategies.

• Mechanization constraints

One of the principal barriers to widespread adoption of intercropping in commercial agriculture is the limited availability of machinery designed for diversified cropping systems. Most

modern agricultural machinery has been developed for monoculture production and is often unsuitable for sowing, weeding and harvesting multiple crops grown together (Sagwal *et al.*, 2022).

Differences in crop height, growth duration and maturity frequently complicate mechanized operations. Harvesting one crop may damage the companion crop, while post-harvest separation of produce can increase labour requirements and operational costs. However, these constraints are less severe in forage-based cereal-legume systems where crops can be harvested simultaneously (Gecaitė *et al.*, 2021).

• Pest and disease risks

Although intercropping generally reduces pest incidence and enhances biological control, certain crop combinations may create favourable conditions for the development and spread of diseases. Dense and diversified canopies can increase humidity and reduce air circulation within the crop stand, thereby promoting fungal diseases under conducive environmental conditions (Khanal *et al.*, 2021) ^[30]. In addition, some component crops may act as alternate hosts for pests and pathogens, potentially increasing disease pressure if crop combinations are not carefully selected. Therefore, understanding crop interactions and disease epidemiology remains essential for successful intercropping management.

• Economic and market constraints

The economic performance of intercropping systems may vary depending on market conditions and crop value. In some cases, the yield of the main crop may decline because of competition from intercrops, which can reduce profitability when the principal crop has substantially higher market value than the companion crop (Chavda *et al.*, 2023). Marketing and processing may also become more complicated when multiple crops are harvested simultaneously. Additional labour requirements for harvesting, sorting and post-harvest handling can increase production costs and reduce economic attractiveness under certain circumstances.

• Research and knowledge gaps

Despite considerable progress in intercropping research, significant knowledge gaps remain regarding crop compatibility, long-term soil health effects, mechanization options and climate resilience under diverse agroecological conditions. Most available studies are location-specific, making it difficult to generalize recommendations across regions. Further research is required to develop mechanization-compatible intercropping systems, precision management approaches and climate-smart intercropping strategies suitable for large-scale adoption.

• Mitigation strategies for intercropping constraints

Many limitations associated with intercropping can be minimized through appropriate management practices. Selection of compatible crop combinations, optimization of planting geometry, balanced nutrient management, adoption of improved mechanization technologies and use of precision agriculture tools can substantially improve system performance. Advances in crop modelling, remote sensing and decision-support systems are expected to further enhance the efficiency and scalability of intercropping systems in the future.

Overall, while intercropping presents several biological and operational challenges, most constraints can be effectively managed through proper system design and agronomic management. Consequently, the benefits of intercropping often outweigh its limitations, particularly in the context of sustainable

and climate-resilient agriculture.

Table 3: Limitation of different intercropping system

Intercropping system	Limitations	References
Row intercropping	Harvesting becomes complex due to different crop maturity; improper combinations may cause interspecific competition and reduce productivity.	(Bybee-Finley <i>et al.</i> , 2018; Maitra <i>et al.</i> , 2021) [8, 35]
Mixed intercropping	Suitable for forage, but separate harvesting of crops is labour-intensive.	(Bybee-Finley <i>et al.</i> , 2018) [8]
Relay intercropping	Lower yield of succeeding crop and higher seed rate required for proper stand.	(Tanveer <i>et al.</i> , 2017)
Strip intercropping	Perennial crops may shade adjacent crops, reducing growth and yield.	(Ryan <i>et al.</i> , 2011)
Additive intercropping	Increased plant density may intensify competition for nutrients, water and light, sometimes reducing main crop yield.	(Willey and Rao, 1980; Khanal <i>et al.</i> , 2021) [30, 66]
Replacement intercropping	Reduced population of component crops may limit yield potential of individual species.	(Mead and Willey, 1980; Francis, 2022) [42, 66]
Alley cropping (agroforestry-based intercropping)	Tree-crop competition for light, water and nutrients; shading and root competition may reduce intercrop yield.	(Hombegowda <i>et al.</i> , 2022; Ryan <i>et al.</i> , 2011)
Multi-storey intercropping	Requires precise management of canopy structure; high competition for light if not properly designed.	(Maitra <i>et al.</i> , 2023; Stomph <i>et al.</i> , 2020) [37, 57]
Cereal-legume intercropping	Nutrient and moisture competition may occur if crop ratios and timing are not optimized.	(Książak <i>et al.</i> , 2023; Gitari <i>et al.</i> , 2019) [19, 32]
Intercropping under mechanized systems	Difficulties in mechanization (sowing, weeding, harvesting) due to crop diversity and spatial arrangement.	(Bybee-Finley and Ryan, 2018; Sagwal <i>et al.</i> , 2022) [8]

Conclusions and future perspectives

Intercropping has emerged as an important strategy for enhancing agricultural productivity while promoting efficient utilization of natural resources and ecological sustainability. The evidence reviewed in this study demonstrates that intercropping systems improve land-use efficiency, resource capture, nutrient cycling, water-use efficiency and overall system productivity through complementary interactions among component crops. By exploiting differences in canopy architecture, rooting patterns and growth duration, intercropping enables more effective utilization of available light, water, nutrients and space than monocropping systems.

Legume-based intercropping systems are particularly beneficial because of their capacity to fix atmospheric nitrogen, improve soil fertility and enhance nutrient availability to associated crops. In addition to productivity gains, intercropping contributes to improved soil health, greater biodiversity, enhanced ecosystem services and reduced dependence on synthetic fertilizers and pesticides. These ecological benefits strengthen the sustainability of agricultural systems and support the conservation of natural resources. Intercropping also plays a significant role in climate-resilient agriculture by improving yield stability, reducing production risks and enhancing the adaptive capacity of farming systems under drought, heat stress and other climatic uncertainties. The diversification of crops within a production system provides biological insurance against environmental fluctuations, thereby improving resilience and livelihood security, particularly in smallholder farming systems. Despite these advantages, the widespread adoption of intercropping is constrained by challenges such as interspecific competition, complex crop management, mechanization limitations and market-related factors. Addressing these constraints requires careful crop selection, optimized planting arrangements, improved agronomic management and the development of machinery suitable for diversified cropping systems.

Future research should focus on understanding crop interactions under changing climatic conditions, developing precision intercropping approaches, integrating digital and remote-sensing technologies, enhancing mechanization options and quantifying long-term impacts on soil health, carbon sequestration and ecosystem services. Greater emphasis should also be placed on designing climate-smart intercropping systems that are

economically viable, environmentally sustainable and adaptable to diverse agroecological conditions. Overall, intercropping represents a scientifically sound and ecologically sustainable approach to agricultural intensification. By simultaneously improving productivity, resource-use efficiency, environmental quality and system resilience, intercropping offers considerable potential for supporting sustainable food production and achieving long-term agricultural and environmental security in the face of growing global challenges.

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