ISSN: 2643-671X

Research Article

Journal of Agriculture and Horticulture Research

Review of Cereal-Legume Intercropping Systems for Sustainable Crop Production

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Submitted: 2026, Jan 21; **Accepted:** 2026, Feb 25; **Published:** 2026, Mar 02

Citation: Ayana, Y., Abebu, Z., Endeshaw, M., Eshetu, S., Alemnew, A., et. al. (2026). Review of Cereal-Legume Intercropping Systems for Sustainable Crop Production. *J Agri Horti Res, 9*(1), 01-05.

Abstract

Cereal-legume intercropping, the simultaneous cultivation of a cereal and a legume on the same piece of land, is a time-tested agroecological practice gaining renewed interest for its potential to enhance agricultural sustainability. This review synthesizes current knowledge on the effects of cereal-legume intercropping on crop productivity, resource use efficiency, soil health, pest and disease dynamics, and socio-economic viability. We examine the underlying ecological mechanisms—including complementary resource use (light, water, and nutrients), biological nitrogen fixation (BNF), and plant-plant interactions—that drive system performance. The paper further examines crucial management strategies, addresses the mechanization challenges inherent to contemporary farming systems, and underscores the integral role of intercropping in building climate-resilient agricultural systems. Evidence overwhelmingly indicates that well-designed cereal-legume intercrops can improve land equivalent ratios (LER >1), reduce synthetic fertilizer dependency, enhance soil fertility, and suppress weeds and pests, thereby contributing to more sustainable and productive farming systems, despite challenges in mechanization and management. Future research should focus on optimizing species/variety combinations, breeding for intercropping compatibility, and developing policies that support the adoption of this multifunctional practice.

Keywords: Intercropping, Sustainability, Land Equivalent Ratio, Nitrogen Fixation, Resource Complementarity, Agroecology, Soil Health, Climate Resilience, Smallholder Agriculture

1. Introduction

Global agriculture faces the unprecedented challenge of producing more food for a growing population—projected to reach 9.7 billion by 2050—while minimizing environmental degradation, reducing reliance on non-renewable inputs, and adapting to climate change. Monoculture-based intensive systems, despite high yields, have often led to soil erosion, biodiversity loss, groundwater pollution, and high greenhouse gas emissions [1]. For instance, synthetic nitrogen fertilizer production and use account for approximately 2.4% of global greenhouse gas emissions [2]. In this context, diversifying cropping systems through practices like intercropping which growing two or more crops simultaneously on the same field—has emerged as a cornerstone of sustainable intensification [3].

Cereal-legume intercropping represents one of agriculture's oldest diversification strategies, with historical roots in traditional farming systems across Asia, Africa, and Latin America. This ancient practice is experiencing renewed scientific and practical interest as a pathway to ecological intensification [4]. It combines a non-leguminous cereal (e.g., maize, sorghum, wheat, barley) with a leguminous species (e.g., soybean, cowpea, common bean, pea, chickpea), leveraging the contrasting growth habits and physiological traits of the two plant families. This paper aim to provide review of the multifaceted effects of cereal-legume intercropping on productivity, resource efficiency, soil health, and socio-economic viability within sustainable crop production systems.

2. Ecological Mechanisms and Principles of Intercropping

The benefits of intercropping stem from fundamental ecological principles that drive system performance through biological synergies rather than chemical inputs.

2.1. Complementary Resource Use

Cereals and legumes often exhibit contrasting above- and below-ground traits that enable more efficient resource exploitation. Cereals typically develop deep root systems and erect canopies, while legumes often feature shallow, spreading roots and broader leaf architectures [5]. This complementarity allows for: (1) more complete light interception through vertically stratified canopies, (2) exploitation of water and nutrients across different soil horizons, and (3) temporal niche differentiation in resource use patterns [4]. Cereals and legumes often have differing rooting architectures (deep vs. shallow) and canopy structures (erect vs. spreading), leading to more efficient exploitation of below-ground resources (water and nutrients across soil profiles) and above-ground resources (light interception through stratified canopies).

2.2. Biological Nitrogen Fixation (BNF)

Legumes, via symbiosis with *Rhizobium* bacteria, fix atmospheric N_2, converting it to plant-available forms. Meta-analyses indicate that legumes can fix between 50-300 kg N ha^{-1} annually depending on species and conditions [6]. A portion of this biologically fixed nitrogen (estimated at 5-25%) transfers to associated cereals through multiple pathways including root exudates, decomposition of legume litter, and shared mycorrhizal networks [7]. This nitrogen transfer significantly reduces the system's dependence on synthetic N fertilizers while minimizing nitrogen losses through leaching and volatilization. Legumes, via symbiosis with *Rhizobium* bacteria, fix atmospheric N_2. A portion of this N can be transferred to the associated cereal through root exudates, decomposition of legume litter, or mycorrhizal networks—a process known as nitrogen transfer. This reduces the system's dependence on synthetic N fertilizers.

2.3. Facilitation and Positive Interactions

Beyond nitrogen, legumes enhance phosphorus availability through rhizosphere acidification and organic anion exudation that mobilize soil-bound phosphorus [5]. Similarly, legumes can increase iron availability through phytosiderophore production and rhizosphere pH modification. These facilitative interactions create positive feedback loops that benefit both intercrop components.

2.4. The "Safety-Net" Effect

The legume component acts as an ecological buffer, capturing mobile nutrients (particularly nitrogen) that might otherwise be lost to leaching, especially following cereal harvest when nutrient uptake capacity diminishes [8]. This safety-net function improves nutrient retention and cycling efficiency within the agroecosystem.

3. Effects on Crop Productivity and Resource Use Efficiency

3.1. Land Productivity and Land Equivalent Ratio

The Land Equivalent Ratio (LER) quantifies intercropping efficiency by comparing the land area required in sole cropping to produce the same yield as achieved in intercropping. An LER > 1 indicates a yield advantage. Well-managed cereal-legume intercrops typically achieve LERs between 1.2 and 1.8, meaning 20-80% more land would be needed in monocultures to produce equivalent yields (Table 1) [9]. This land-saving effect is particularly valuable for smallholder farmers with limited land resources. The Land Equivalent Ratio (LER) is the standard metric for evaluating intercropping efficiency. An LER > 1 indicates a yield advantage over sole crops.

Cereal Component	Legume Component	Region/Country	LER Range	Reference
Maize	Cowpea	Semi-arid Africa	1.3-1.7	Rusinamhodzi et al., 2012 [10].
Wheat	Chickpea	South Asia	1.2-1.6	Singh et al., 2019 [11].
Sorghum	Pigeon pea	India	1.4-1.8	Ghosh et al., 2020 [12].
Barley	Faba bean	Mediterranean	1.3-1.5	Bedoussac et al., 2015 [13].
Maize	Common bean	Latin America	1.2-1.6	Letourneau et al., 2011 [14].

Table 1: Cereal-Legume Intercrops and Their Reported Land Equivalent Ratios

3.2. Nitrogen Use Efficiency (NUE)

Cereal-legume intercrops consistently demonstrate enhanced nitrogen use efficiency, with NUE improvements ranging from 20-50% compared to sole crops [8]. The cereal component benefits from legume-fixed nitrogen, enabling reduced synthetic N application while maintaining or increasing yields. The legume may experience reduced biological nitrogen fixation in high-N soils but typically maintains yield stability through alternative nitrogen acquisition strategies.

3.3. Water Use Efficiency (WUE)

Complementary root systems and enhanced ground cover improve soil moisture conservation through reduced evaporation and increased infiltration. In semi-arid regions, cereal-legume intercrops have demonstrated 15-30% higher water use efficiency compared to sole crops [15]. The legume's soil shading reduces surface evaporation, while cereal roots access deeper water reserves.

3.4. Light Interception and Radiation Use Efficiency

The stratified canopy architecture characteristic of many cereal-legume intercrops improves light distribution within the system. Cereal canopies intercept high-intensity light at the top, while understory legumes utilize diffuse and transmitted light. This tiered structure reduces wasteful light saturation on cereal leaves and increases total system radiation use efficiency by 10-25% [16].

4. Impacts on Soil Health and Fertility

4.1. Soil Organic Matter and Carbon Sequestration

Diversified root systems with varying biochemical compositions contribute heterogeneous organic inputs to the soil. Legume residues, with their lower C:N ratios (typically 15:1 to 25:1 compared to 50:1 to 80:1 for cereals), decompose more rapidly and promote the humification of cereal-derived carbon [17]. Meta-analyses indicate that well-managed intercrops can increase soil organic carbon stocks by 5-15% compared to sole crops, though outcomes depend on residue management, climate, and system duration [18].

4.2. Soil Biological Activity

Intercropping enhances soil microbial biomass, diversity, and functional activity. Studies report 20-40% increases in microbial biomass carbon and nitrogen under intercrops compared to sole crops [19]. Enzyme activities critical for nutrient cycling—including dehydrogenase, phosphatase, and urease—typically increase by 15-30% in intercropped systems [20]. The amplified "rhizosphere effect" from two contrasting root systems fosters more diverse and functionally redundant microbial communities that enhance nutrient cycling and suppress soil-borne pathogens.

4.3. Soil Physical Properties

Enhanced root biomass from intercropping systems improves soil aggregation through root exudation of binding agents and physical entanglement. Intercrops typically increase water-stable aggregates by 10-25% and reduce bulk density by 5-15% compared to sole crops [21]. These improvements in soil structure enhance infiltration capacity (increasing by 20-40%) and reduce surface runoff and erosion, particularly on sloping lands.

5. Pest, Disease, and Weed Dynamics

5.1. Weed Suppression

Intercrops create denser, more complex canopies that shade the soil earlier and more completely than sole crops. This physical suppression reduces weed biomass by 40-75% compared to monocultures [22]. The ecological weed management provided by intercrops significantly reduces herbicide requirements, particularly important for organic systems and herbicide-resistant weed management.

5.2. Pest Regulation

Increased plant diversity disrupts host-finding behavior through the "resource concentration hypothesis" [23]. Insect pest populations in intercrops are typically 30-50% lower than in sole crops, though effects are species-specific [15]. Intercrops also provide enhanced habitat and alternative food sources for natural enemies, increasing predator and parasitoid populations by 20-40%. However, in some cases, intercrops can create "green bridges" that maintain pest populations between seasons or alter microclimates to favor certain pests, highlighting the need for context-specific design.

5.3. Disease Management

Non-host plants in intercrops create physical barriers that reduce splash dispersal of fungal and bacterial pathogens by 30-60% [24]. Altered microclimates—particularly reduced humidity within the canopy—can inhibit certain foliar diseases. However, some intercrop combinations may increase humidity at lower canopy levels, potentially exacerbating certain diseases, underscoring the importance of species selection and spatial arrangement.

6. Socio-Economic and Livelihood Benefits

6.1. Risk Reduction and Resilience

Intercropping diversifies production, buffering farmers against total crop failure due to biotic or abiotic stresses. Field studies demonstrate that intercrops reduce yield variability by 20-40% compared to sole crops, providing more stable production across variable growing conditions [25]. This risk-spreading function is particularly valuable in climate-vulnerable regions with increasing weather variability.

6.2. Nutrition and Food Security

Farmers harvest multiple nutrient-dense products from the same field, enhancing dietary diversity and household nutrition. The cereal-legume combination provides complementary proteins, with cereals supplying methionine and legumes providing lysine—creating a nutritionally complete protein source when consumed together [26]. Intercrops typically increase household dietary diversity scores by 15-25% in smallholder farming communities [27].

6.3. Economic Viability and Input Costs

Reduced requirements for synthetic nitrogen fertilizers (by 30-50%) and pesticides (by 20-40%) significantly lower production costs [28]. Economic analyses indicate that despite potentially higher labor requirements, intercrops improve profit margins by 15-30% compared to sole crops, particularly when both crop components have market value [10].

7. Management Considerations and Challenges

7.1. Design Factors

Successful intercropping requires careful consideration of multiple design elements:

- Species and variety selection: Matching complementary phenology, architecture, and resource use patterns
- Spatial arrangement: Optimizing row ratios, orientation, and spacing (additive vs. replacement designs)
- Temporal synchronization: Aligning planting dates and growth cycles to maximize complementarity
- Density optimization: Balancing competition and facilitation through appropriate planting densities

7.2. Mechanization Challenges

Harvesting remains the primary mechanization challenge, particularly for grain intercrops. Promising solutions include:

- Breeding for synchronized maturity and uniform plant architecture
- Developing strip-intercropping systems compatible with

existing machinery
- Focusing on forage/fodder intercrops that can be harvested together
- Designing novel harvesting equipment for mixed stands

7.3. Nutrient Management

While nitrogen requirements decrease, careful management of phosphorus, potassium, and micronutrients remains essential. Competition for these non-mobile nutrients can be intense, particularly in low-fertility soils. Site-specific nutrient management strategies, potentially incorporating precision application technologies, are needed to optimize intercrop performance.

7.4. Knowledge-Intensive Nature

Optimal intercrop management is highly context-specific, requiring sophisticated ecological knowledge and observational skills. This knowledge-intensity presents adoption barriers, particularly where extension services are limited. Participatory research approaches and farmer-to-farmer learning networks have proven effective in developing and disseminating locally adapted intercrop management practices [27].

8. Role in Climate Change Mitigation and Adaptation

8.1. Mitigation Potential

Cereal-legume intercrops contribute to climate change mitigation through multiple pathways:

- Reduced fertilizer emissions: Lower synthetic N use decreases direct N_2O emissions (by 30-50%) and indirect emissions from fertilizer production [29].
- Enhanced carbon sequestration: Increased soil organic carbon storage represents a significant carbon sink
- Reduced fossil fuel use: Lower input requirements decrease energy consumption across the production chain

8.2. Adaptation Benefits

Intercrops enhance climate resilience through:

- Improved water management: Complementary root systems and ground cover buffer against drought stress
- Risk diversification: Multiple crop species provide insurance against climate extremes
- Microclimate moderation: Denser canopies reduce temperature extremes and evaporation
- Pest and disease resilience: Enhanced biodiversity creates biological buffers against climate-mediated pest outbreaks.

9. Future Research Directions

- Breeding for Intercropping Compatibility: Developing crop varieties specifically selected for performance in mixed stands, focusing on traits like shade tolerance, complementary architecture, and facilitative root exudation.
- Precision Intercropping Management: Leveraging remote sensing, IoT sensors, and machine learning to optimize in-season management decisions, including precision nutrient application and irrigation scheduling.
- Ecosystem Service Quantification: Developing robust methodologies to value non-yield benefits including carbon sequestration, water quality protection, and biodiversity conservation for potential inclusion in ecosystem service markets.
- Value Chain Development: Researching market incentives, collective harvesting and processing systems, and consumer products specifically designed for intercrop outputs to improve economic viability.
- Policy Integration Framework: Developing coherent policy packages including subsidies, crop insurance products, and market linkages that incentivize intercropping adoption at scale.
- Mechanization Innovations: Designing harvesting and processing equipment specifically for intercrop systems to reduce labor constraints.

10. Conclusion

Cereal-legume intercropping represents a paradigm shift in agricultural thinking—from a singular focus on individual crop yields to a systems perspective that values multiple dimensions of sustainability. By harnessing ecological principles of complementarity and facilitation, intercrops deliver synergistic benefits across productivity, resource efficiency, soil health, and farm resilience. While management challenges persist, particularly regarding mechanization and knowledge requirements, ongoing research and innovation are developing solutions for wider adoption. The integration of cereal-legume intercropping into mainstream agricultural policy and practice represents not a regression to traditional methods but a progression toward farming systems that are simultaneously productive, profitable, and environmentally harmonious. As global agriculture confronts the interconnected challenges of food security, environmental sustainability, and climate resilience, cereal-legume intercropping offers a scientifically grounded, practically viable pathway toward truly sustainable crop production in the 21st century.

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