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Cereal–Legume Intercropping: An Ecologically Sound Strategy for Enhancing System Productivity and Sustaining Soil Health

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ABSTRACT

The growing global demand for food, coupled with concerns over soil degradation, declining resource-use efficiency, and environmental pollution, necessitates the development of sustainable cropping systems. Conventional monocropping systems reliant on heavy application of synthetic nitrogen fertilizers have led to deterioration of soil health, increased greenhouse gas emissions, and loss of biodiversity. Cereal–legume intercropping has emerged as a viable agroecological approach that enhances system productivity through complementary resource use and biological nitrogen fixation. Legumes contribute atmospheric nitrogen to the system, while cereals efficiently utilize soil nutrients, water, and solar radiation. This review critically examines the principles, spatial configurations, nitrogen dynamics, productivity indices, and constraints associated with cereal–legume intercropping systems, with particular emphasis on maize–soybean-based combinations. Evidence from diverse agro-ecological regions suggests that well-designed cereal–legume intercropping systems improve yield stability, reduce fertilizer nitrogen requirements, enhance soil fertility, and provide economic resilience to farmers, especially under rainfed and resource-constrained conditions.

Keywords : Intercropping, Cereals, Legumes, Biological Nitrogen Fixation, System productivity, Soil sustainability

Introduction

Agriculture in the twenty-first century faces the dual challenge of increasing food production to meet the needs of a growing population while conserving natural resources and ensuring environmental sustainability. Agricultural intensification based on cereal monocropping, heavy mechanization, and extensive use of synthetic fertilizers has contributed significantly to global food security. However, these gains have been accompanied by soil degradation, declining soil organic matter, nutrient imbalance, reduced factor productivity, and increased environmental pollution (Willey, 1979; Vandermeer, 1992), raising concerns about the long-term sustainability of input-intensive cereal-based systems. Cereals form the backbone of global food systems,

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occupying a major share of cultivated land and supplying most dietary energy. Continuous cereal monocropping has led to progressive depletion of soil nutrients, particularly nitrogen, the most yield-limiting element in cropping systems. To compensate, farmers increasingly depend on synthetic nitrogen fertilizers. While fertilizers enhance short-term productivity, inefficient nitrogen use results in losses through leaching, volatilization, and denitrification, increasing environmental degradation and production costs (Ofori and Stern, 1987; Jensen, 1996). Declining nitrogen-use efficiency underscores the need for alternative strategies that sustain productivity while reducing external inputs. Cropping system diversification has therefore emerged as a key component of sustainable intensification. Diversified systems are generally more resilient, resource-efficient, and environmentally benign than monocropping systems. Among diversification approaches, intercropping—the simultaneous cultivation of two or more crops on the same field for a significant part of their growth cycle—has received renewed scientific attention (Willey, 1979; Rao and Willey, 1980). Intercropping enables biological interactions among component crops, leading to more efficient use of light, water, nutrients, and space than sole cropping. Intercropping is based on ecological principles such as niche differentiation, competition, facilitation, and complementarity (Vandermeer, 1992). Differences in canopy structure, rooting pattern, phenology, and nutrient requirements allow component crops to exploit resources more completely across time and space, resulting in higher productivity and greater yield stability (Rao and Willey, 1980; Willey and Rao, 1980). Consequently, intercropping is increasingly recognized as a scientifically validated strategy for sustainable intensification. Cereal–legume intercropping systems are particularly important due to strong functional complementarities. Cereals are high-yielding crops with high nitrogen demand, whereas legumes fix atmospheric nitrogen through symbiosis with rhizobia (Jensen, 1996; Giller, 2001). This reduces competition for soil nitrogen and improves nitrogen-use efficiency at the system level (Bedoussac and Justes, 2010). Although direct nitrogen transfer during the growing season is limited, cereals benefit indirectly from reduced competition and nitrogen release following decomposition of legume residues (Giller, 2001; Lithourgidis *et al.*, 2011). Beyond nitrogen dynamics, cereal–legume systems exhibit complementarities in canopy architecture and root distribution. Cereals intercept direct solar radiation, while legumes efficiently utilize diffused light (Hauggaard-Nielsen *et al.*, 2001). Differences in rooting depth enable better exploitation of soil resources and reduce competition (Vandermeer, 1992; Bedoussac *et al.*, 2015), while temporal differences in growth further enhance resource partitioning.

These systems provide multiple agronomic, ecological, and economic benefits, including higher land-use efficiency, improved yield stability, enhanced soil fertility, reduced weed pressure, and lower dependence on synthetic fertilizers (Ghosh, 2004; Lithourgidis *et al.*, 2011). Increased crop diversity also enhances soil biological activity and agroecosystem functioning (Brooker *et al.*, 2015). Despite strong evidence of their benefits, adoption of cereal–legume intercropping remains limited due to management complexity, lack of suitable varieties, mechanization challenges, and inadequate extension support (Lithourgidis *et al.*, 2011; Layek *et al.*, 2014). Evaluation using appropriate biological and economic indices is therefore essential for objective assessment of system productivity and sustainability (Rao and Willey, 1980; Willey and Rao, 1980). In view of these considerations, the present review synthesizes existing knowledge on cereal–legume intercropping, emphasizing its conceptual basis, resource-use complementarity, nitrogen dynamics, productivity responses, and evaluation indices, while also highlighting constraints and future research directions for integrating these systems into sustainable and climate-resilient agricultural production systems (Bedoussac *et al.*, 2015; Brooker *et al.*, 2015).

Concept and Objectives of Intercropping

Intercropping refers to growing of two or more crop species simultaneously on the same field for a significant portion of their growth cycle, allowing biological interactions among component crops. Unlike crop rotation or sequential cropping, intercropping involves temporal and spatial overlap of crops, which enables more efficient use of environmental resources (Willey, 1979; Vandermeer, 1992). The fundamental objective of intercropping is to enhance total system productivity per unit land area and time through improved resource capture and utilization. From an ecological standpoint, intercropping represents the applied manifestation of key ecological principles such as niche differentiation, competition, facilitation, and complementarity (Vandermeer, 1992). When crops differing in morphology, growth dynamics, rooting behavior, and nutrient requirements are grown together, they tend to exploit resources more efficiently and comprehensively than when grown as sole crop. This often results in yield advantages and greater stability under variable environmental conditions (Rao and Willey, 1980). Intercropping systems may be classified based on spatial arrangement and temporal overlap. Common forms include row intercropping, strip intercropping, mixed intercropping, and relay intercropping. Among these, row intercropping is the most widely studied and adopted form due to ease of management and compatibility with mechanization (Willey, 1979). Strip intercropping allows independent management of component crops while still permitting interspecific interactions, whereas mixed intercropping relies on random spatial distribution and is often practiced in traditional farming systems. Another important classification is based on crop population density, namely additive and replacement series intercropping. In additive series, the base crop is maintained at its full population while the intercrop is introduced by modifying crop geometry, often resulting in higher land-use efficiency (Rao and Willey, 1980). In replacement series, populations of both crops are reduced proportionally, which may lower competition but also reduce yield advantage (Willey and Rao, 1980). The scope of intercropping extends beyond yield improvement. Properly designed intercropping systems enhance biodiversity, improve soil structure, reduce weed pressure, and increase resilience to climatic stress (Vandermeer, 1992; Brooker *et al.*, 2015). These multifunctional benefits make intercropping a cornerstone of sustainable and climate-resilient agricultural systems.

Principles of Successful Cereal + Legume Intercropping

The following principles should be followed for success of a cereal + legume intercropping -

(i) The time of peak nutrient demands of component crops should not be overlapped. For example, in maize + greengram intercropping system, the peak nutrient demand period for greengram is around 35 days after sowing while it is 50 days for maize.

(ii) There should be minimum competition for light among the component crops. As all the plants use the same resources like light, water, nutrients etc. there is competition within and between the species for these resources. The legume being forced to rely on N2 fixation when the non-legume is more competitive for soil inorganic nitrogen (N). It suits best, if the cereal crops (taller) are sun loving plants and the intercropped legumes (shorter height) are shade tolerant plants.

(iii) Complementarity should exist between the component crops. Complementary use of growth resources in both time and space was seen as possible explanations. The most important relation between cereals and legumes is the N-use complementarity (Ofori and Stern, 1987; Jensen, 1996). For example, in cereal+legume intercropping, the legumes can use atmospheric nitrogen, while the associated cereal crops mostly depend of their nitrogen from the soil sources. Some part of the fixed nitrogen by the legumes also being shared to the cereals, hence there is more of complementarity and less of competition for nitrogen for the associated crops.

(iv) There should be difference in maturity for component crops by at least 30 days for least completion in intercropping.

When cereals and legumes are grown as intercrops in an intercropping system, each of them should have adequate space to maximize use of resources and minimize competition between them. For making the cereal + legume intercropping system a successful one, spatial arrangement, plant density and plant architecture must be considered.

Types of Intercropping and Change in Crop Geometry

There are four basic spatial arrangements used in intercropping.

Row intercropping - Growing two or more crops simultaneously in the field with at least one crop planted in rows. Most of the improved agricultural practices throughout the world using this concept.

Strip intercropping - Growing two or more crops together in strips wide enough to permit separate crop production using machines but close enough for the crops to interact.

Mixed intercropping - Growing two or more crops together without any distinct row arrangement. Seeds of different crops were mixed before planting and generally sown by randomly broadcasting them in the field. The mixed intercropping is

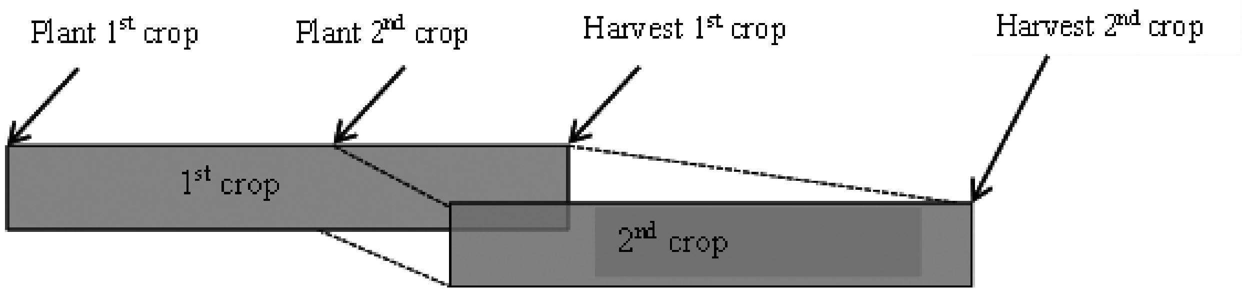
Maize + Ground nut intercropping

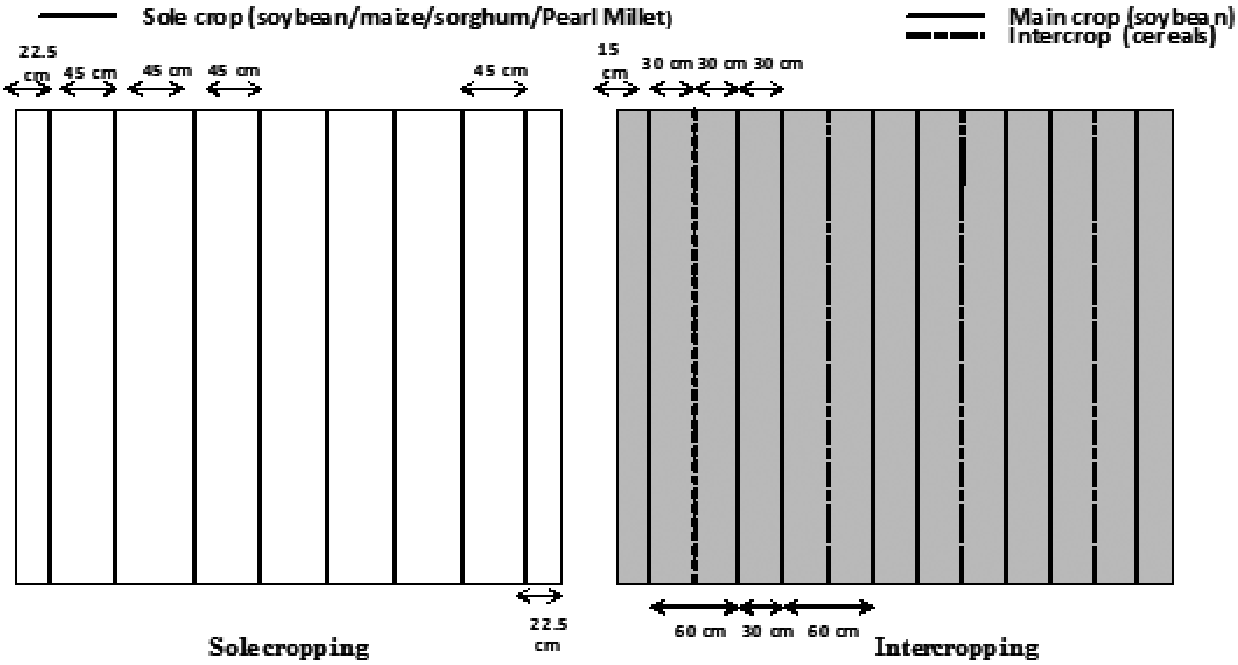
Maize + Soybean intercropping

Maize + Cowpea intercropping

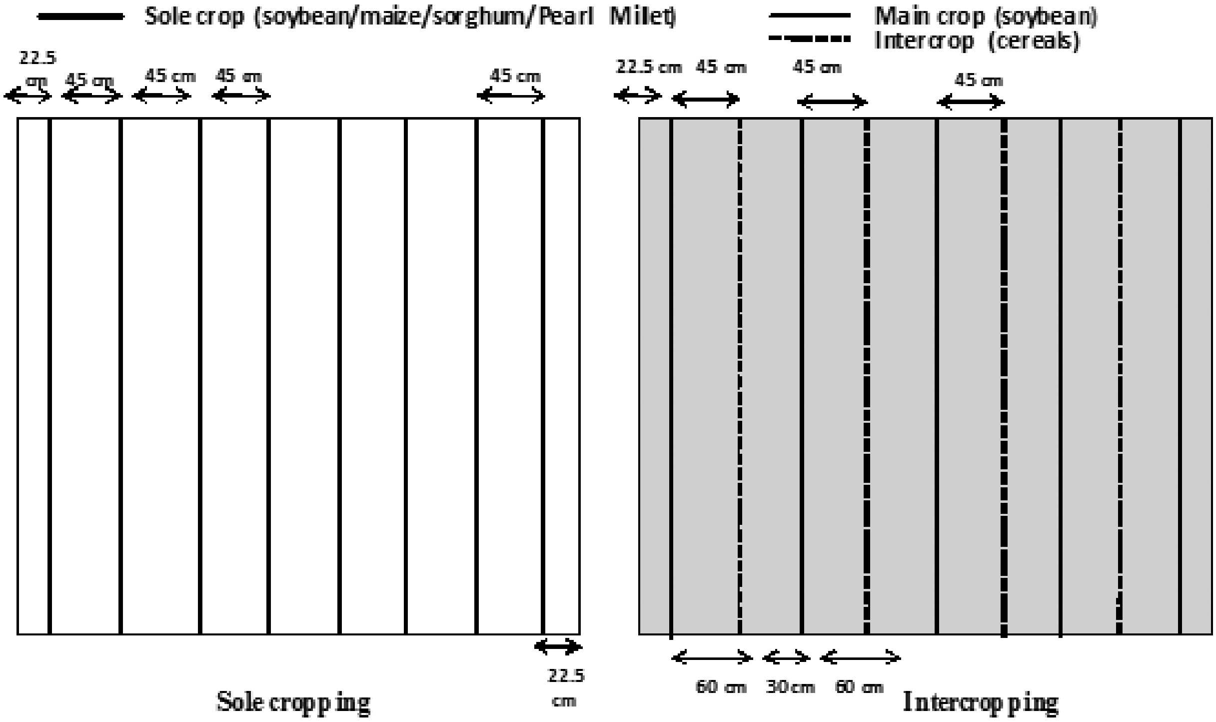
generally used in agriculturally less developed countries to meet the diverse need of food products from the limited area of land. It is also being used in pasture to provide diversified products to grazing animals. Cultivation in Slash and Burn Agriculture (Shifting cultivation), where farmers used to grow 10-12 crops in a particular land, the mixed cropping is the best example for that.

Relay intercropping - Planting a second crop into a standing crop at a time when the standing crop is at its reproductive stage but before harvesting. In areas, where the crop growing season is limited to grow two discrete sequential crops in succession, relay intercropping permits to grow two separate crops successfully from the same land within a year. By sowing the succeeding 2nd crop before harvesting the proceeding crop (standing situation), the second crop gets a good start on its growing season and able to mature in due time. In other areas, where generally double-cropping is practiced, but aberrant weather situation or shortage of labor or machine availability may delay harvest of the first crop and subsequent planting of the second crop — this relay intercropping can play a great role to obtain two crops from the same field within a calendar year.





Planting geometry of sole crops and soybean+cereal intercropping (2:1) in additional sereies.



Planting geometry of sole crops and soybean+cereal intercropping (1:1) in replacement sereies.

Cereal–Legume Intercropping as an Ecological Intensification Strategy

Cereal–legume intercropping is among the most widely practiced and scientifically validated intercropping systems due to its strong ecological foundation. Cereals and legumes differ fundamentally in their nutrient acquisition strategies, growth habits, and physiological traits, enabling complementary use of resources when grown together (Ofori and Stern, 1987; Jensen, 1996). Legumes possess the unique ability to fix atmospheric nitrogen through symbiosis with rhizobial bacteria, whereas cereals rely almost entirely on soil mineral nitrogen. This functional differentiation reduces direct competition for soil nitrogen and improves nitrogen-use efficiency at the system level (Giller, 2001; Bedoussac and Justes, 2010). As a result, cereal–legume intercropping systems often require lower nitrogen fertilizer inputs than cereal monocropping systems (Lithourgidis *et al.*, 2011). In addition to nitrogen complementarity, cereal–legume systems exhibit aboveground and belowground complementarities. Cereals typically develop taller canopies and intercept direct sunlight, while legumes occupy lower canopy layers and efficiently utilize diffused radiation (Hauggaard-Nielsen *et al.*, 2001). Rooting patterns also differ, allowing exploitation of different soil strata and reducing direct competition for water and nutrients (Vandermeer, 1992). Cereal–legume intercropping contributes to ecological intensification by enhancing productivity while reducing environmental externalities. Increased plant diversity improves ecosystem functioning, supports beneficial soil microorganisms, and enhances nutrient cycling (Brooker *et al.*, 2015). These systems thus align closely with sustainable intensification goals that emphasize productivity gains through ecological processes rather than increased input use.

Resource-Use Complementarity in Cereal–Legume Intercropping Systems

Resource-use complementarity is the primary mechanism underlying yield advantages in cereal–legume intercropping systems. Complementarity occurs when component crops differ in their temporal or spatial use of growth resources, enabling more complete capture and utilization of available light, water, nutrients, and space (Vandermeer, 1992; Bedoussac *et al.*, 2015). Aboveground complementarity is reflected in improved light interception due to vertical stratification of canopies. Cereals intercept direct radiation at upper canopy levels, while legumes exploit diffused light at lower levels, enhancing overall photosynthetic efficiency (Hauggaard-Nielsen *et al.*, 2001). Temporal differences in canopy development further reduce self-shading and light loss. Belowground complementarity arises from differences in root architecture and depth distribution. Cereals typically exploit surface soil layers efficiently, whereas legumes often develop deeper or more branched root systems, accessing subsoil moisture and nutrients (Vandermeer, 1992). Such spatial differentiation reduces competition and improves water-use efficiency, particularly under rainfed conditions.

Complementarity in nutrient uptake extends beyond nitrogen. Legume root exudates can enhance phosphorus availability and stimulate microbial activity, indirectly benefiting associated cereals (Bedoussac and Justes, 2010). These synergistic interactions contribute to higher system productivity and resilience.

Nitrogen Dynamics and Biological Nitrogen Fixation

Nitrogen dynamics are central to the functioning and sustainability of cereal–legume intercropping systems. Biological nitrogen fixation enables legumes to convert atmospheric nitrogen into plant-available forms, reducing reliance on soil nitrogen pools (Jensen, 1996; Giller, 2001). In intercropping systems, cereals benefit indirectly from legume nitrogen fixation primarily through reduced competition for soil nitrogen rather than direct nitrogen transfer during the growing season (Giller, 2001). However, decomposition of legume residues contributes significantly to soil nitrogen availability for subsequent crops (Lithourgidis *et al.*, 2011). Nitrogen fertilizer management is critical in cereal–legume intercropping. Excessive nitrogen application increases cereal dominance, suppresses legume nodulation, and reduces system-level benefits (Bedoussac and Justes, 2010). Optimized nitrogen management enhances productivity while maintaining ecological balance.

Productivity, Yield Stability, and Competition Effects in Cereal–Legume Intercropping

Productivity enhancement is a primary objective of cereal–legume intercropping systems, and numerous studies have reported higher total yields and land-use efficiency compared to sole cropping. The productivity advantage of intercropping is often quantified using indices such as the land equivalent ratio, which frequently exceeds unity in cereal–legume systems, indicating superior land-use efficiency. Cereal yields in intercropping systems often increase or remain comparable to sole cropping due to improved access to soil nitrogen, light, and water. Legume yields, however, may be reduced as a result of shading and competition exerted by cereals. The extent of yield reduction depends on cereal aggressiveness, plant density, spatial arrangement, and nitrogen management. Aggressive cereals such as sorghum and pearl millet tend to exert stronger competitive pressure on associated legumes than maize or wheat. Yield stability is another important advantage of cereal–legume intercropping systems. Diversification of crop species reduces vulnerability to climatic variability, pest outbreaks, and disease incidence. In years with unfavourable weather conditions, one component crop may compensate for the reduced performance of the other, resulting in more stable overall yields compared to monocropping systems.

Competition between component crops is an inherent feature of intercropping systems and must be carefully managed to ensure complementarity outweighs competition. Competition for light is often the dominant factor influencing legume performance, particularly when tall cereals are grown at high density or receive excessive nitrogen fertilization. Competition for water and nutrients can also be significant, especially under resource-limited conditions. Balancing competition and complementarity require careful selection of crop species and cultivars, optimization of planting geometry, and appropriate nutrient management. Adjusting row spacing, planting dates, and nitrogen application rates can help mitigate excessive competition and improve overall system performance.

Indices for Measuring Productivity and Efficiency in Cereal–Legume Intercropping Systems

Quantitative assessment of cereal–legume intercropping systems is essential to understand the extent of yield advantage, competitive interactions, and economic feasibility relative to sole cropping systems. Because intercropping involves multiple component crops, conventional yield comparisons are inadequate, necessitating the use of specialized biological and economic indices. These indices provide insights into land-use efficiency, interspecific competition, and overall system performance.

The **Land Equivalent Ratio (LER)** is the most widely used index in intercropping research. It expresses the relative land area required under sole cropping to achieve yields equivalent to those obtained in an intercropping system. An LER value greater than unity indicates a yield advantage of intercropping, reflecting more efficient resource use. In cereal–legume intercropping systems, LER values frequently exceed one, demonstrating superior land-use efficiency.

Crop Equivalent Yield (CEY) converts yields of component crops into the yield of a single reference crop based on prevailing market prices. This index allows comparison of biological productivity in economic terms and is particularly useful for evaluating farmer profitability. Higher CEY values in intercropping systems indicate better economic returns despite possible yield reduction of individual component crops.

Indices such as **Aggressivity**, **Relative Crowding Coefficient (RCC)**, and **Competition Ratio (CR)** are used to assess dominance relationships and competitive intensity between component crops. Cereals often exhibit positive aggressivity values, confirming their dominant role, whereas legumes generally show negative aggressivity, indicating suppression. RCC values greater than unity suggest yield advantage, whereas values below one indicate excessive competition.

Actual Yield Loss (AYL) provides information on yield gain or loss of each component crop on a per-plant basis, offering deeper insight into inter- and intra-specific competition. The **Monetary Advantage Index (MAI)** integrates economic returns with biological productivity and is particularly relevant for decision-making at the farm level.

Together, these indices form a comprehensive framework for evaluating cereal–legume intercropping systems and are indispensable tools for researchers and practitioners.

Constraints, Opportunities and Future Perspectives of Cereal–Legume Intercropping

Despite substantial agronomic and ecological benefits, adoption of cereal–legume intercropping systems remains limited in many production environments. One major constraint is **management complexity**, as intercropping requires careful planning of crop combinations, planting geometry, nutrient management, and harvesting operations. Mechanization challenges, particularly in planting and harvesting, further discourage adoption in large-scale farming systems. Soil-related constraints such as acidity, nutrient deficiencies, and poor rhizobial effectiveness can limit legume performance and reduce system benefits. Inadequate access to quality seeds, lack of site-specific recommendations, and weak extension support also hinder widespread adoption. Additionally, limited market incentives for diversified produce reduce economic motivation for farmers. Despite these challenges, cereal–legume intercropping offers significant opportunities in the context of climate change, rising input costs, and sustainability goals. Advances in crop breeding, development of compatible cultivars, precision nutrient management, and mechanization-friendly designs can substantially enhance system performance. Policy support, capacity building, and participatory research approaches will be critical for scaling up adoption.

Constraints and Adoption Challenges

Despite strong evidence supporting the agronomic and ecological benefits of cereal–legume intercropping, adoption remains limited in many regions. Major constraints include soil-related limitations such as acidity and nutrient deficiencies, lack of access to quality seeds and inputs, increased management complexity, labour requirements, and challenges associated with mechanization and harvesting. Inadequate extension services, limited market incentives for diversified produce, and insufficient policy support further restrict adoption (Matusso *et al.*, 2014). Addressing these constraints through integrated soil fertility management, development of suitable machinery, farmer participatory research, and supportive policy frameworks is essential for large-scale adoption.

Conclusion

Cereal–legume intercropping represents a scientifically validated and environmentally sustainable approach for enhancing agricultural productivity while conserving soil health across diverse agro-ecological regions. Through complementary resource use, improved nitrogen dynamics, and enhanced resilience to climatic variability, these systems offer a viable alternative to input-intensive monocropping. Wider adoption of cereal–legume intercropping can significantly contribute to sustainable food security, reduced fertilizer dependency, climate change mitigation, and long-term soil fertility maintenance.

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