



REVIEW ARTICLE

Intercropping for sustainable agriculture: Ecological, agronomical and socioeconomic perspectives

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Abstract

Intercropping, the simultaneous cultivation of two or more crops on the same land, is a vital strategy for achieving sustainable, resilient and resource-efficient agriculture. By exploiting spatial and temporal complementarities, intercropping enhances biodiversity, nutrient cycling and ecosystem services while minimising environmental impacts. The practice significantly improves land productivity, often reflected by Land Equivalent Ratios (LER) greater than 1.2, indicating superior yield per unit area compared to monocultures frequently reported. Integrating legumes with cereals reduces synthetic nitrogen fertiliser requirements by up to 60 %, thereby lowering greenhouse gas emissions and enhancing soil fertility. Ecologically, intercropping fosters beneficial microbial communities, enhances arbuscular mycorrhizal activity and improves soil organic carbon and nutrient-use efficiency. Agronomically, it suppresses weeds, pests and diseases through diversified canopy structure and allelopathic interactions, while enhancing water-use efficiency and drought resilience in some crop combinations. Socioeconomically, intercropping diversifies farm income, mitigates risks and strengthens smallholder livelihoods. Case studies across Asia, Africa and Europe demonstrate substantial productivity gains, improved soil health and higher carbon sequestration in cereal-legume and agroforestry-based systems. Despite these benefits, challenges such as management complexity, limited mechanisation compatibility and inadequate policy support constrain large-scale adoption. Future directions emphasise breeding for intercropping-suitable cultivars, integrating precision agriculture and digital tools and implementing supportive policy frameworks. As a nature-based solution, intercropping represents a key component cornerstone for sustainable intensification, contributing to climate change mitigation, food security and ecological resilience.

Keywords: agroecology; biodiversity; carbon sequestration; climate resilience; intercropping; legumes; nutrient-use efficiency; productivity; resource optimisation; soil health; sustainable intensification

Introduction

Intercropping, defined as the simultaneous cultivation of two or more crop species in the same field and during the same growing season, is a widely recognised component of diversified and ecologically intensive farming systems (1, 2). This practice harnesses spatial and temporal complementarities among crops to optimise the use of natural resources such as light, water and nutrients, while minimising biotic and abiotic stresses (3). In contrast to highly simplified monoculture systems that prioritise uniformity, intercropping leverages biodiversity-driven ecological interactions to enhance system resilience and productivity, representing a shift toward multifunctional and sustainable agroecosystems (4). Historically, intercropping has been practised for centuries by smallholder farmers across Asia, Africa and Latin America as a risk-buffering strategy against crop failure and environmental

variability (5, 6). Traditional systems such as maize-bean in Latin America, sorghum-pigeon pea in Africa and rice-pulses systems in Asia illustrate the deep agroecological knowledge underlying crop combinations (7, 8). However, with the onset of industrial agriculture and the Green Revolution, intercropping practices declined in favour of input-intensive monocultures designed for mechanisation and uniform management (9). In recent decades, mounting concerns over soil degradation, biodiversity loss and climate instability have renewed scientific and policy interest in intercropping as a nature-based solution for sustainable intensification (10, 11)

Globally, intercropping is now being recognised as a strategic pathway for climate-resilient and resource-efficient food systems. Its benefits span multiple dimensions: higher land productivity, enhanced nutrient cycling, reduced pest and disease incidence and greater income stability for farmers through improved

land equivalent ratio (LER) which can be defined as the sum of the partial yield ratios of component crops in an intercrop relative to their respective sole crop yields, representing the relative land area required under monoculture to match intercrop productivity, (2, 12). In Europe and China, modern intercropping systems such as cereal-legume or maize–soybean combinations have demonstrated yield advantages and reduced nitrogen fertiliser requirements, contributing to sustainable nitrogen management (3, 13). In sub-Saharan Africa and South Asia, intercropping continues to serve as a pillar of smallholder resilience, improving food security, soil health and ecosystem services under variable climatic conditions (14, 15). Despite its proven ecological and economic advantages, scaling intercropping remains constrained by challenges related to mechanisation, breeding for interspecific compatibility and limited policy incentives (16, 17). Addressing these limitations requires interdisciplinary approaches integrating agronomy, ecology, socioeconomics and digital technologies to design context-specific and scalable intercropping models. As global agriculture faces the dual imperatives of producing more food with fewer resources and reducing environmental impacts, intercropping emerges as a promising framework for the next generation of sustainable farming systems (3, 11).

Literature review methodology

A systematic literature survey methodology was used to conduct this review, using keywords such as "intercropping," "cereal-legume systems," "land equivalent ratio," "agroecological intensification" and "climate-resilient agriculture." Peer-reviewed publications were obtained from the Web of Science, Scopus and Google Scholar databases. Publications from 1990 to 2024 were given priority, with a focus on long-term field trials, meta-analyses and experimental studies. Excluded were studies with no quantitative agronomic or ecological results. To assess the ecological, agronomic and socioeconomic effects of intercropping systems, about 60 studies were screened and 55 important publications were compiled.

Types of intercropping systems

Intercropping involves growing two or more crops simultaneously on the same piece of land, to improve land-use efficiency, productivity, resource utilisation and ecological sustainability (2). Intercropping systems are primarily classified based on spatial arrangement and temporal overlap of the component crops. The major types include mixed intercropping, row intercropping, strip intercropping, relay intercropping, alley cropping, patch intercropping (spatial clustering) and multistorey or vertical intercropping. Each system exhibits distinct interactions between crops and contributes differently to ecosystem services and productivity (3, 18). The conceptual framework illustrating the mechanism and agro-ecological outcome of a sustainable intercropping system is presented in Fig. 1.

Mixed intercropping

Definition and mechanism: Mixed intercropping, or polyculture (1, 18), refers to growing two or more crops together without a defined row pattern. Plants are randomly intermixed, allowing high plant density and fine-scale complementarity in resource use (2). In such systems, crops can exploit differences in root depth, nutrient acquisition, canopy height and phenology. For example, a shallow-rooted legume can fix nitrogen that is later available to a deeper-rooted cereal, while also reducing soil erosion and suppressing weeds (6).

Examples: Traditional cereal-legume mixtures such as millet + cowpea, sorghum + pigeon pea or smallholder home-garden polycultures in India and Africa exemplify mixed intercropping. These systems are often used where labour is plentiful, mechanisation is limited and risk diversification is critical.

Advantages:

- Enhanced land-use efficiency and overall productivity (3).
- Increased biodiversity, which reduces pest and disease incidence.
- Improved soil fertility, particularly when legumes are included.

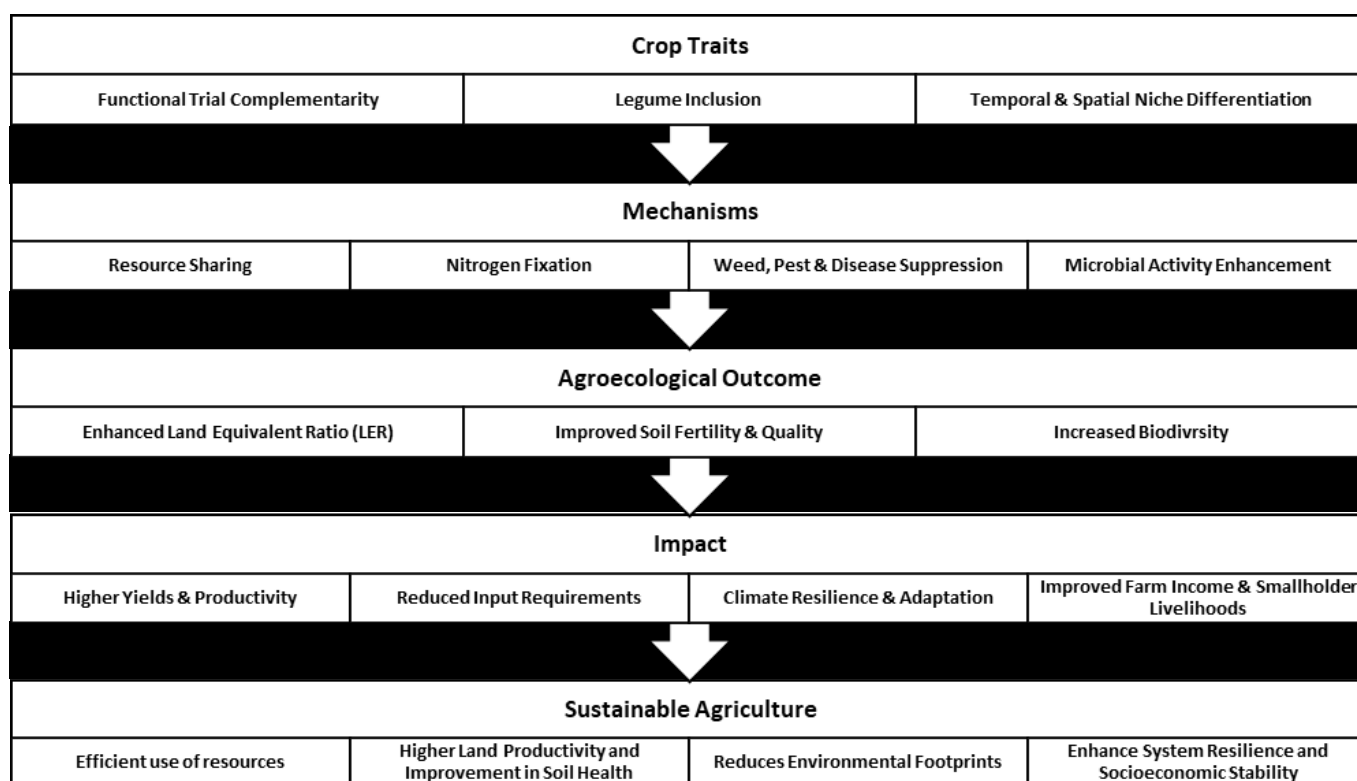


Fig. 1. Framework for sustainable intercropping.

Constraints:

- Difficult mechanisation due to irregular plant arrangement.
- Complex management for irrigation, fertilisation and harvesting.
- Yield assessment is challenging, separation of crop products at harvest is labour-intensive (2).

Row intercropping

Definition and mechanism: In row intercropping, crops are grown in distinct, alternating rows, enabling controlled competition and facilitation. Row spacing can be adjusted to optimise light interception, water use and nutrient acquisition (16). Legumes intercropped with cereals often transfer biologically fixed nitrogen to the cereal, enhancing growth without chemical fertiliser input (19).

Examples:

- Maize-bean or wheat-pea systems in temperate and tropical regions.
- Rice-azolla systems, where azolla is grown concurrently with rice and functions as a nitrogen-fixing intercrop that suppresses weeds and contributes biomass; in some systems, it is also used as livestock feed.

Advantages:

- Easier mechanisation of planting and harvesting.
- Facilitation effects between crops, particularly nitrogen transfer from legumes to cereals.
- Pest and disease management through crop heterogeneity.

Constraints:

- Competition may increase if row spacing is not optimised.
- Requires careful timing and proportioning of component crops.
- May need additional labour for weed control between rows (2).

Strip intercropping

Definition and mechanism: Strip intercropping involves planting crops in blocks or strips several rows wide, allowing independent management while still enabling ecological interactions at strip edges. Strips facilitate resource complementarity, particularly in light and water capture, while remaining compatible with mechanised farming (20).

Examples:

- Maize-soybean strips, where maize dominates the taller canopy and soybeans occupy lower layers.
- Cereal-forage strips for livestock feed production.

Advantages:

- Compatible with mechanisation.
- Optimises inter-species interactions while maintaining operational flexibility.
- Reduces risk from pest outbreaks through edge effects.

Constraints:

- Edge benefits are limited if strips are too wide.
- Requires knowledge of crop interaction distances to avoid competition.

- Management complexity increases with the number of species (3).

Relay intercropping

Definition and mechanism: Relay intercropping is a temporal intercropping system, where a second crop is sown into an existing crop before the first is harvested. This creates partial overlap, optimising land-use across the growing season (21). Temporal staggering reduces competition for light, nutrients and water and ensures continuous ground cover, mitigating erosion.

Examples:

- Cereal-legume relay systems, such as sorghum interplanted with cowpea a few weeks before sorghum harvest.
- Rice-mung bean relay systems in tropical Asia.

Advantages:

- Efficient land utilisation and continuous production.
- Risk diversification and extended harvest periods.
- Enhances soil protection and nutrient cycling.

Constraints:

- Requires precise timing of sowing.
- Relay crop may suffer from shading or reduced establishment.
- More management-intensive than sole cropping (2).

Alley cropping

Definition and mechanism: Alley cropping combines perennial woody species with annual crops in defined alleys. Trees contribute to organic matter, nutrient cycling, hydraulic lift and microclimate regulation, while crops exploit space between alleys (22). Pruning regimes are critical to prevent excessive shading and competition.

Examples:

- Leucaena-maize and Gliricidia-cassava systems in smallholder farms.
- Tropical home-gardens integrating fruit trees and tuber crops.

Advantages:

- Multifunctional: produces timber, fodder and green manure.
- Enhances soil fertility and water-use efficiency.
- Improves resilience to climatic extremes and pest pressure.

Constraints:

- Long-term establishment, delayed economic returns.
- Requires careful pruning and tree management.
- Potential shade competition if species are not compatible (23).

Patch intercropping

Definition and mechanism: Patch intercropping, which entails the spatial organisation of crops dividing them into discrete clusters or blocks within a single field. This type of intercropping predominantly transpires through species interaction at patch boundaries and mitigating direct interspecific competition within clusters, making them appropriate for heterogeneous areas where microtopography or soil variability affects crop positioning.

Example: Taro + sweet potato + legume patches in smallholder farms.

Advantages:

- Reduced direct competition within patches.
- Flexibility in crop placement according to soil or moisture gradients.
- Potential for partial mechanisation depending on patch size.

Constraints:

- Edge effects depend on patch dimensions.
- Management complexity increases with species diversity.
- Yield estimation may be spatially variable.

Multistorey or vertical intercropping

Definition and mechanism: Multistorey intercropping, or vertical intercropping, entails the cultivation of crops with differing canopy heights, rooting depths and growth durations to optimise vertical niche differentiation. Species are organised in layers, facilitating the optimal utilisation of solar energy, soil nutrients and water across various vertical strata. This approach frequently replicates forest structure and is prevalent in tropical agroforestry and home garden systems.

Example: Coconut + banana + pineapple in humid tropics

Advantages:

- Efficient utilisation of vertical space.
- Enhanced biodiversity and ecological resilience.
- Continuous and diversified production across seasons.

Constraints:

- High management and pruning requirements.
- Shade competition if poorly designed.
- Limited compatibility with large-scale mechanisation.

System selection considerations

The selection of the intercropping type depends on:

Ecological complementarity: differences in root depth, phenology and canopy structure.

Labour and mechanisation availability: strip and row systems suit mechanised farms, mixed systems suit smallholder farms.

Climate and soil conditions: water-limited or nutrient-poor soils benefit more from facilitative interactions.

Market and production goals: crop choice depends on whether income, subsistence, or ecosystem services are prioritised (2, 18).

Optimal design requires integrating spatial and temporal patterns, selecting compatible crop species and evaluating performance using metrics such as land equivalent ratio (LER), relative yield total (RYT) and competitive indices (23, 24).

Design principles for successful intercropping

Across the studies, successful intercropping system follows some common principles:

(i) Complementarity of functional traits among component crops, such as deep-rooted crops are intercropped with shallow rooted crops, crops with different critical growth and maturity dates stages are combined to manage them better.

(ii) Differentiation of spatial or temporal niches, such as wider spaced crops, are combined with crops having narrower row spacing and crops with different heights are grown together to harness the sunlight effectively

(iii) Incorporation of legumes for enhancing soil fertility through biological nitrogen fixation and increasing organic content

(iv) optimised input use efficiency

(v) adaptive management in line with local agroecology. These guidelines offer a framework for creating robust systems and identifying productive intercrops from competitive mixtures.

Ecological and agronomic benefits of intercropping

Enhanced biodiversity and ecosystem functioning

Intercropping enhances α - (within-field) and β - (between-field) biodiversity across multiple trophic levels by creating spatial and temporal heterogeneity in canopy structure, root architecture, litter composition and flowering phenology (25). Such heterogeneity provides niches for a variety of organisms, including pollinators, predatory insects, soil fauna and microbial communities, ultimately supporting multiple ecosystem services (26). At the belowground level, intercropping fosters diverse microbial communities with higher functional redundancy and enzymatic activity, particularly for nitrogen (N) and phosphorus (P) cycling. Increased microbial diversity and activity enhance nutrient mineralisation, soil aggregation and resilience to environmental stressors (27). For example, long-term experiments with legume-cereal intercrops have reported up to a 35 % increase in arbuscular mycorrhizal colonisation compared to monoculture systems, improving nutrient uptake efficiency and plant growth (2). Aboveground, intercropping creates stratified canopies and staggered flowering times, which support pollination and natural enemy populations.

The presence of flowering legumes and companion plants provides nectar and pollen resources that sustain beneficial insects throughout the growing season, contributing to biological pest control and enhanced pollination (25). Moreover, biodiversity in intercropping systems stabilises productivity under environmental variability. By combining species with complementary traits such as deep versus shallow-rooted crops or early versus late-maturing species, intercropped systems buffer against abiotic stresses (drought, heat and nutrient limitation), thereby enhancing ecosystem resilience and stability (6). Overall, intercropping acts as a nature-based intensification strategy, enhancing ecosystem functioning, supporting beneficial organisms and contributing to more resilient and sustainable agricultural landscapes.

Soil health improvement and biogeochemical cycling

Intercropping enhances soil health by promoting structural, chemical and biological improvements in the rhizosphere. The presence of multiple species with contrasting root morphologies and turnover rates increases soil aggregation, reduces compaction and enhances cation exchange capacity, thereby improving soil fertility and water-holding capacity (3). Deep-rooted crops access subsoil nutrients, while shallow-rooted species exploit topsoil resources, creating complementary nutrient capture patterns that reduce intra-specific competition and improve overall nutrient-use efficiency. Integration of legumes into intercropping systems contributes to biological nitrogen fixation, reducing synthetic nitrogen fertiliser requirements by 25–60 % and enhancing rhizobial colonisation and soil mineral N availability (3). Legumes also increase

the protein content of residues returned to the soil, which accelerates microbial decomposition and nutrient cycling. Intercropping systems have been shown to increase SOC by 0.1–0.4 Mg C ha⁻¹ yr⁻¹, depending on residue management, crop biomass allocation and species combinations (28). Higher soil organic carbon improves nutrient retention, soil moisture buffering and microbial habitat quality. Belowground interactions in the rhizosphere, including organic acid exudation and arbuscular mycorrhizal (AM) symbioses, enhance phosphorus mobilisation and uptake, lowering dependency on non-renewable phosphate fertilisers (2). These biological processes, combined with litter decomposition and root turnover, create positive feedback for soil fertility, structural stability and long-term resilience of agroecosystems. By improving soil physical, chemical and biological properties simultaneously, intercropping fosters sustainable nutrient cycling, enhanced fertility and reduced environmental footprint, making it a cornerstone practice for climate-smart agriculture.

Pest and disease suppression through ecological regulation

Intercropping disrupts pest population build-up by modifying visual cues, volatile organic compound (VOC) profiles and host plant accessibility. Push-pull and trap cropping systems have demonstrated significant reductions in infestation rates of fall armyworm, pod borers and whiteflies (25). Yield losses from pests can be reduced by 20–40 % in intercrops compared to single-species stands and pathogen pressure is mitigated through canopy stratification and microclimate adjustment that reduce humidity-driven disease outbreaks. Natural enemy abundance and parasitism rates can be up to 50 % higher in diversified systems.

Water use efficiency and drought mitigation

Intercropping enhances water use efficiency (WUE) and mitigates drought stress through complementary root architecture, canopy stratification and hydraulic interactions among co-cultivated species. In multi-species systems, deep-rooted legumes oilseeds or vegetables access subsoil water, while shallow-rooted cereals, exploit topsoil moisture, minimising competition and optimising overall water capture (3, 28). Hydraulic lift in deep-rooted crops redistributes water from wetter subsoil layers to drier upper layers, indirectly benefiting neighbouring shallow-rooted crops and improving nutrient mobility (29). Such complementary interactions stabilise soil moisture during dry periods and buffer crop productivity against erratic rainfall events. Field studies indicate that intercropping can improve WUE by 10–35 % relative to monocultures, especially under limited irrigation or rainfed conditions (28, 30). Diverse canopies and continuous ground cover reduce evaporative losses and soil surface runoff, increasing effective precipitation use and promoting infiltration. Furthermore, intercropping moderates microclimate and soil temperature, reducing evapotranspiration and stress on crop physiology (30, 31). Species selection with complementary phenology and canopy layering enhances drought resilience, particularly in semi-arid and water-limited regions. Collectively, these mechanisms position intercropping as a climate-smart strategy for water management and resilience.

Climate resilience and system stability

The inherent diversification in intercropping systems enhances climate resilience by reducing yield variability and buffering against abiotic stressors such as temperature extremes, irregular rainfall and heat waves (6). Complementary species responses create insurance

effects, where stress-tolerant crops compensate for yield losses in more sensitive species, stabilising overall system productivity. This stabilising effect is particularly evident in legume-cereal and multi-strata systems, where differential rooting depth, phenology and water use patterns mitigate drought and heat stress impacts (3, 30). Intercropping also contributes to climate change mitigation. Reduced synthetic nitrogen fertiliser use lowers nitrous oxide (N₂O) emissions, while carbon stored in above and below-ground biomass, combined with increased SOC from diverse residues, enhances carbon sequestration (32, 33). Multi-strata and agroforestry-based intercropping systems can sequester 2–6 Mg CO₂e ha⁻¹ yr⁻¹, depending on tree density, species turnover and management practices (34). Beyond carbon benefits, intercropping increases ecosystem stability by enhancing soil structure, promoting beneficial microbial communities and improving water-use efficiency, all of which buffer crops against climate variability. Modelling studies suggest that diversified intercropping systems can reduce yield risk under projected climate scenarios, particularly in semi-arid and rainfed regions (35, 30). By combining productivity gains with resilience and mitigation co-benefits, intercropping offers a holistic, climate-smart strategy for sustainable agriculture.

Synergistic interactions and productivity gains

Intercropping systems often exhibit synergistic interactions that translate into significant productivity gains compared to monocultures. The land equivalent ratio (LER) is a widely used metric to quantify these advantages. LER values exceeding 1.2 indicate that intercropped systems produce 20–40 % more biomass per unit land area than sole crops (2, 3). Mechanisms underlying these gains include complementarity in light interception, canopy layering, root distribution and phenological timing. For instance, taller cereals can capture sunlight from upper canopy layers, while shorter legumes utilise filtered light, enhancing photosynthetically active radiation (PAR) use efficiency across the system (30). Differential rooting depths reduce competition for soil, water and nutrients, allowing crops to exploit distinct soil horizons and improve overall resource capture. In cereal-legume systems, field experiments have documented grain yield improvements of 15–25 % and protein content increases of up to 18 % without additional fertiliser or irrigation inputs (28). Similarly, intercropping maize with cowpea or soybean has increased total system productivity by 30–35 %, demonstrating strong complementarity in nutrient acquisition and light use (30). These synergistic effects also contribute to yield stability under environmental stress, as resource partitioning allows intercropped systems to buffer against temporal fluctuations in temperature, rainfall and soil nutrient availability (6). Consequently, intercropping is recognised as a climate-smart intensification strategy, offering both higher productivity and greater resilience without increasing external input demands.

Reduction in external inputs and environmental footprint

Intercropping, particularly when involving legumes, reduces the need for synthetic nitrogen inputs through biological nitrogen fixation and facilitation effects. Legume-cereal intercrops can substitute 20–60 % of mineral nitrogen fertiliser while maintaining or improving yield stability (2, 3). Diverse root architectures improve resource partitioning and nutrient capture, while rhizosphere acidification and enzymatic activity enhance phosphorus solubilisation and micronutrient availability (26). The reduction in fertiliser application leads to measurable declines in nitrous oxide emissions and energy-intensive fertiliser production. Species

diversity in intercropping modifies pest behaviour, disrupts vector movement and enhances populations of natural enemies. Canopy stratification, volatile organic compound interference and non-host barrier effects suppress insects and pathogens without chemical intervention (25). In systems such as maize–beans, sorghum–legume and rice–mustard intercrops, reductions of 20–50 % in pesticide use have been reported. Furthermore, allelopathic and smothering species can reduce weed competition, decreasing herbicide dependence and soil contamination risk (6).

By curbing synthetic inputs, intercropping lowers life cycle greenhouse gas emissions associated with fertiliser manufacture, pesticide synthesis and field application. Field studies indicate that diversified systems improve nitrogen-use efficiency and decrease nitrate leaching and runoff, reducing eutrophication and groundwater pollution (28). Enhanced soil organic matter and improved microbial functioning contribute to circular nutrient use and reduce external energy demands. The cumulative effect is a smaller environmental footprint per unit of production and stronger alignment with low-carbon agricultural pathways.

Case studies in intercropping

Maize-cowpea intercropping in Sub-Saharan Africa

A study conducted in Côte d'Ivoire evaluated the performance of maize (*Zea mays*) and cowpea (*Vigna unguiculata*) intercropping systems under different row orientations. The findings indicated that intercropping improved land-use efficiency and provided economic benefits compared to monocultures. The combined LER was 1.18, suggesting an 18 % increase in productivity per unit area. Additionally, intercropping enhanced crop access to nitrogen and phosphorus, improving nutrient use efficiency (36).

Wheat-maize intercropping with reduced tillage in China

Research at the Wuwei Research Station in China assessed the impact of wheat-maize intercropping combined with reduced tillage and straw retention. The study found that this integrated approach enhanced both economic and environmental benefits, including improved soil health and increased crop yields. The system also contributed to carbon sequestration and reduced greenhouse gas emissions (37).

Agroforestry systems in Southern Ontario, Canada

In southern Ontario, Canada, tree-based intercropping systems involving hybrid poplar and Norway spruce intercropped with barley were studied. The results demonstrated that these systems contributed significantly to carbon sequestration, with carbon stocks in the soil reaching up to 77.37 t ha⁻¹ (38).

Maize-soybean intercropping in the North China Plain

A study in the North China Plain evaluated the yield performance of maize–soybean intercropping systems. The findings indicated that intercropping systems outperformed monocultures in terms of yield and resource use efficiency, highlighting the benefits of intercropping in enhancing productivity (39).

Barley-chickpea intercropping with superabsorbent polymers

Research on barley-chickpea intercropping systems treated with superabsorbent polymers showed that this combination increased biological yield compared to monocultures. The study suggests that integrating such technologies can further enhance the benefits of intercropping (40).

Several studies across different agro-ecological regions have demonstrated the benefits of intercropping in terms of productivity, soil health and resource-use efficiency. Representative case studies are summarised in Table 1.

Table 1. Case studies in intercropping

Case study	Key findings (concise)	References
Maize × cowpea / Guinea savanna - Northern Ghana	Maize-grain-legume intercropping increased resource-use efficiency, total productivity and economic return vs sole crops, improved N-use and LER >1.	41
Maize × soybean (row/strip systems) - Southwest China	Maize-soybean intercropping raised maize yield stability and nutrient uptake across phosphate regimes, improved soil physico-chemical and enzymatic activity.	42
Maize × soybean (subtropical) - China	Intercropping increased nutrient uptake, modified soil properties and improved yield compared to monocultures under local management.	43
Maize × faba bean (different densities) Tigray, Ethiopia (semiarid)	Maize intercropped with faba bean (50 % faba bean density) increased total grain yield, income and soil N and SOC vs sole maize, LERs 1.11–1.38.	44
Global meta/field synthesis - multiple cereals and legumes	Intercropping produces diverse products with productivity similar to the best sole crop while adding stability and other ecosystem services (comprehensive analysis).	3
Wheat × pea (cultivar combinations) - Greece	Choice of cultivar pair strongly affects mixture performance; some wheat×pea cultivar combinations achieved very high LERs and grain yields - varietal selection is critical.	45
Pea × wheat (low-input Europe) - multi-site experiments	Pea-wheat intercrops provided higher economic performance and lower environmental impacts than sole crops in low-input systems (better land use and N dynamics).	46
Millet × soybean + bio-fertiliser - Serbia (alternating rows/strips)	Millet-soybean intercropping with microbial inoculants increased LER (>1), improved grain quality (Fe, Mn) and lowered potentially toxic elements in millet.	47
Maize × soybean - Red soil, China (phosphate experiments)	Maize-soybean intercropping improved yield stability and sustainability under varying phosphate application rates, useful for low-input systems.	48
Maize × soybean (microbiome study) - China	Intercropping altered rhizosphere microbiome: increased soil nutrients and reduced plant pathogen abundance, correlating with improved maize growth traits.	44
Sorghum × legumes (multi-year sorghum-Bambara/cowpea system) - South Africa	Two-year sorghum-legume intercrop showed distinct, persistent core fungal communities; intercropping influenced beneficial/detrimental fungi with implications for resilience.	49
Eco-functional intensification: cereal-grain legume trials (58 experiments, Europe)	Review + dataset synthesis: cereal-legume intercrops increase productivity via niche complementarity, improved N use and weed suppression, provides design principles for organic systems.	16
Meta-analysis (33 studies) - intercropping and yield stability	Meta-analysis shows intercropping generally enhances yield stability across arable production systems - quantifies stability gains and drivers.	6
Teff × faba bean (mixed cropping) - Ethiopian highlands	Teff-faba bean mixed systems increased total productivity and land-use efficiency relative to sole crops in highland smallholder systems.	50
Common millet × soybean (alternating rows/strips, with/without bio-fertiliser) - Serbia	Alternating-strip intercropping + bio-fertiliser achieved the highest LER (≈1.38) and improved antioxidant content and micronutrient accumulation, good for dryland/low-input agroecology.	48

Socioeconomic impacts of intercropping

Farmer income diversification

Intercropping enables farmers to cultivate multiple crops simultaneously, providing diverse income streams and reducing dependency on a single commodity. Studies have shown that cereal-legume intercrops can increase net farm income by 15-30 % compared to monocultures, largely due to complementary yields and reduced input costs in many smallholder and low-input systems (4). By diversifying crop portfolios, smallholder farmers in regions like Sub-Saharan Africa and South Asia can stabilise household income while ensuring food security.

Risk mitigation

Crop diversification inherent in intercropping acts as a hedge against environmental and market risks. When one crop fails due to drought, pests, or disease, the companion crop often compensates for the loss, reducing overall financial vulnerability. Meta-analyses indicate that intercropping systems can reduce yield variability by 20-35 %, enhancing resilience against climate extremes (6).

Labour and resource optimisation

Intercropping facilitates efficient utilisation of labour, land and inputs. By synchronising crop phenology, farmers can optimise planting, weeding and harvesting operations. In the mechanised and semi-mechanised systems, intercropping improves land-use efficiency without significantly increasing labour requirements in well designed system (26). Additionally, the synergistic effects of nutrient-use complementarity and pest suppression reduce the need for external fertilisers and pesticides, lowering production costs.

Market access and crop demand

By producing multiple crops simultaneously, intercropping systems enable farmers to tap into diverse markets, meeting both local food needs and higher-value niche markets. For example, maize-legume or vegetable-legume intercrops often yield products with enhanced nutritional quality, fetching premium prices in some markets (3). Such market flexibility enhances profitability and strengthens the socioeconomic sustainability of farming systems.

Technological and research advances in intercropping

Breeding for intercropping

The development of crop varieties specifically adapted to intercropping systems is critical for maximising yield advantages and system resilience. Traditional breeding often focuses on monoculture performance, which may not capture the complementary interactions necessary in intercropped environments. Recent advances include selecting for traits such as plant height, phenology, nutrient-use efficiency and root architecture, which optimise resource partitioning in intercropped systems (13). Integrating multi-trait selection with genomic prediction models accelerates the development of intercropping-compatible cultivars, particularly for legume-cereal systems.

Agroecological modelling

Modelling tools are increasingly employed to simulate intercropping outcomes under diverse environmental conditions. Models such as DSSAT (decision support system for agrotechnology transfer) and APSIM (agricultural production systems simulator) can predict yield, resource-use efficiency and carbon sequestration for various crop combinations (3). Although crop simulation models such as DSSAT and APSIM have been widely applied in diverse cropping systems,

representing interspecific competition and facilitative processes in intercropping remains challenging due to increased structural complexity and parameterisation demands (17). These tools support the optimisation of row arrangements, planting densities and species combinations to maximise productivity and ecological benefits while minimising resource inputs.

Precision agriculture tools

Precision agriculture technologies, including remote sensing, GPS-guided machinery, variable-rate application systems and UAVs (drones), are increasingly applied to intercropping systems. These tools facilitate site-specific management of nutrients, irrigation and pest control, thereby improving system efficiency and sustainability (30). Coupled with data-driven decision-making platforms and machine learning algorithms, precision tools allow farmers to manage spatial and temporal heterogeneity inherent in intercrops, enhancing yield stability and resource-use efficiency.

Soil health monitoring

Maintaining soil health is fundamental for productive and sustainable intercropping systems. Recent research has highlighted the use of high-throughput soil sensors, spectroscopy and microbial community profiling to monitor soil organic carbon, nutrient availability and microbial diversity (30). Such approaches provide real-time insights into nutrient cycling, soil structure and microbial dynamics, enabling targeted interventions to sustain soil fertility and system productivity over time.

Policy and institutional framework for intercropping

Supportive policies

Government policies play a pivotal role in promoting intercropping adoption. Incentives such as subsidies for seed diversity, crop insurance schemes and payments for ecosystem services can encourage farmers to diversify cropping systems. In countries like India and China, policy measures that integrate climate-smart agriculture practices have demonstrated positive impacts on intercropping uptake, enhancing productivity while mitigating environmental risks (10). Policies that recognise the multifunctionality of intercropping, including soil fertility improvement, carbon sequestration and biodiversity conservation, are essential for scaling up adoption. For example, the National Mission for Sustainable Agriculture (NMSA) of India, for instance, encourages varied and climate-resilient cropping techniques, such as intercropping and integrated farming systems (51). Similar to this, the Common Agricultural Policy (CAP) of the European Union includes agri-environmental programs and greening initiatives that encourage ecological intensification and crop variety (52).

Extension services

Agricultural extension services are crucial for translating research into practice. Extension programmes that provide field demonstrations, farmer field schools and participatory training increase farmers' understanding and adoption of intercropping practices. Evidence from Sub-Saharan Africa shows that interactive extension approaches significantly improve farmers' capacity to manage intercropping systems efficiently, reducing risks associated with knowledge gaps (53).

Farmer education and training

Education and capacity-building initiatives are central to empowering farmers to implement and optimise intercropping systems. Training programmes focused on species selection,

planting arrangements, pest and nutrient management and market linkages enhance technical competence and decision-making. Studies indicate that farmer education on benefits, economic potential and ecological functions of intercropping increases adoption rates and long-term sustainability (26).

Research and development

Continued investment in research and development (R & D) is essential to address current limitations and advance intercropping technologies. R & D priorities include breeding varieties suited for intercropping, optimising cropping patterns for different agroecologies and integrating digital tools for precision management. Collaborative efforts between universities, research institutions and government agencies have shown potential in generating locally adapted intercropping models that maximise productivity and ecosystem services (5).

Challenges and limitations of intercropping

Management complexity

Intercropping systems are inherently more complex than monocultures, requiring careful planning of crop selection, spatial arrangement, planting dates and nutrient management. Mismanagement can lead to intra-specific competition, reduced yields or pest outbreaks (4). Farmers must balance complementarity in light, water and nutrient use while considering temporal and spatial interactions between species. This complexity can be a barrier, particularly for smallholder farmers with limited labour or mechanisation capacity.

Market constraints

While intercropping enhances farm resilience and nutritional diversity, it can pose challenges in marketing. Farmers may face difficulties in simultaneously selling multiple crops or meeting quality standards required for commercial markets (6). The lack of aggregation systems or value chains for minor crops can reduce profitability, discouraging adoption despite agronomic benefits.

Knowledge and skill requirements

Effective intercropping demands advanced agronomic knowledge and practical skills. Farmers must understand species interactions, pest and disease dynamics, soil fertility management and harvest timing. Without adequate extension support and training, the potential benefits of intercropping may not be fully realised (26). Adoption is often higher among farmers with prior exposure to participatory field trials and demonstration plots.

Policy and institutional support

The adoption of intercropping is strongly influenced by policy and institutional frameworks. Inadequate incentives, lack of access to quality seeds and limited support for research and extension services can hinder scaling of intercropping systems (10). Policies that fail to recognise the multifunctional benefits of intercropping, such as soil health improvement, carbon sequestration and biodiversity enhancement, can result in low adoption rates despite clear ecological advantages.

Environmental performance metrics

The environmental sustainability of intercropping systems can be evaluated by metrics including carbon footprint, SOC, nutrient usage efficiency (NUE) and life-cycle assessment (LCA). Legume-based intercrops can replace 20–60 % of mineral nitrogen inputs,

consequently diminishing nitrous oxide emissions and decreasing energy consumption linked to fertiliser manufacturing (31). Enhanced residue return and root biomass result in SOC increases of 0.2–0.5 Mg C ha⁻¹ yr⁻¹ relative to monoculture, hence improving soil structure and water retention.

Nutrient absorption and biological nitrogen fixation result in a 20–40 % increase in overall nitrogen recovery while minimising leaching losses (31, 36). Life-cycle assessments consistently demonstrate reduced global warming potential, eutrophication and acidification impacts per production unit compared to monocultures (16, 47). Standardising these environmental indicators can enhance evidence-based policy formulation and promote the incorporation of intercropping into climate and sustainability frameworks.

Future directions and research needs in intercropping

Climate change adaptation

Intercropping has significant potential to buffer cropping systems against climate variability, including droughts, heat stress and erratic rainfall. Future research should focus on species selection and combination strategies that maximise system resilience under projected climate scenarios. Integrating intercropping with climate-smart practices, such as conservation tillage, water-saving irrigation and agroforestry, can enhance both productivity and carbon sequestration (30, 54). Modelling approaches can identify optimal species combinations to mitigate climate risks in diverse agroecologies.

Economic analysis

While intercropping is agronomically advantageous, comprehensive economic assessments are required to evaluate profitability, labour requirements and risk reduction. Future research should use cost-benefit analyses, LER-based productivity evaluation and life-cycle assessments to quantify the economic and environmental trade-offs of intercropping versus monoculture systems (4). Such studies will guide farmers and policymakers in scaling up economically viable intercropping models.

Policy development

Supportive policies are critical to enhance the adoption of intercropping systems. Future efforts should focus on incentivising diversification, providing risk insurance, supporting research and strengthening extension services. Integrating intercropping into sustainable agriculture and climate adaptation strategies can increase both adoption and ecosystem service delivery (10). Evidence-based policy frameworks should also address market access for diverse crops and provide subsidies for intercropping-specific inputs and technologies.

Technology integration

Advances in precision agriculture, remote sensing, IoT-based soil monitoring and AI-driven decision support systems offer opportunities to optimise intercropping management. Future research should explore real-time monitoring of soil health, nutrient status and pest pressures, enabling dynamic and site-specific interventions (30). The integration of genomic tools, crop modelling and sensor-based irrigation can enhance yield stability and resource-use efficiency in complex intercropping systems.

Conclusion

Intercropping represents a strategically essential technique for promoting sustainable and climate-resilient agricultural systems. By promoting biodiversity, improving soil health, optimising water and nutrient utilisation and stabilising yields, intercropping contributes to both ecological intensification and socioeconomic resilience across varied agroecosystems. Multi-strata and legume-based systems further increase carbon sequestration and reduce reliance on synthetic inputs, aligning intercropping with low-carbon development pathways.

Despite its proven benefits, widespread adoption remains restricted by management complexity, market limits and insufficient governmental and institutional backing. Addressing these difficulties demands continuous investment in producing intercrop-compatible cultivars, increasing precision agriculture tools, strengthening extension services and integrating intercropping into national sustainability and climate plans. With coordinated efforts among researchers, politicians and farming communities, intercropping can serve as a cornerstone of productive, environmentally sound and resilient agricultural systems.

The creation of intercrop-specific cultivars, standardised performance metrics and decision-support tools that combine ecological and economic indicators ought to be the top priorities of future research. Precision agriculture tools and extension services can help farmers adopt and profit from location-specific crop combinations. Intercropping should be encouraged by policymakers through climate-smart agriculture frameworks, ecosystem-service payments and diversification incentives. Scaling intercropping as a common sustainable intensification strategy will require coordinated research, policy and farmer collaboration.

Authors' contributions

PP carried out the literature survey and drafted the manuscript. CC and TK contributed to the compilation of intercropping practices and data interpretation. SP analysed the sustainability aspects and prepared the manuscript. CB, KS and SS assisted in the critical revision of the manuscript and editing. VKS conceived the study, supervised the work and finalised the manuscript. All authors read and approved the final manuscript.

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Declaration of generative AI and AI-assisted technologies in the writing process

In the preparation of this manuscript, AI-assisted technologies were utilised to support various aspects of the writing process. Specifically, tools such as Paperpal, SciSpace, TrinkAI and Zotero were employed to assist with language refinement, literature review, reference management and overall manuscript organisation. These technologies were used as supportive aids to enhance clarity, consistency and efficiency; however, all conceptualisation, analysis, interpretation and final content remain the original work of the authors.

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