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Boosting resource use efficiency, soil fertility, food security, ecosystem services, and climate resilience with legume intercropping: a review

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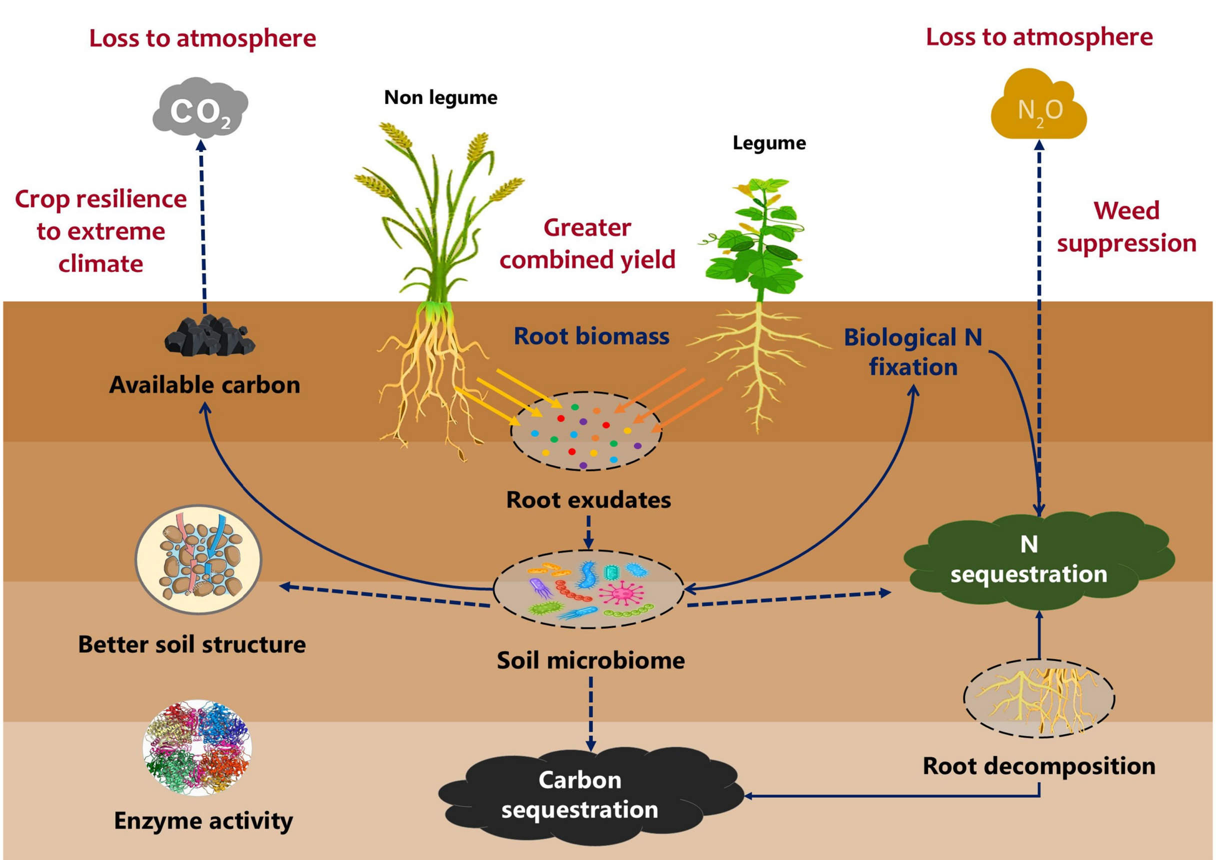
Adopting sustainable agricultural practices that enhance productivity while preserving ecosystem services is essential to ensure food security for a growing global population and address environmental challenges. This review examines the impact of legume intercropping on nitrogen (N) fixation, soil physio-chemical properties, water retention, pest and disease control, and crop yield across diverse agro-climatic zones and cropping systems. The findings consistently demonstrate that integrating legumes into the cropping system improves soil health by reducing bulk density, breaking up hardpan layers, reducing erosion, increasing soil organic matter, and fixing atmospheric nitrogen (~125 kg N/ha/season) reducing the need for inorganic N fertilizers. It boosts crop yields by 30–35% (in terms of main crop equivalent yield) and land productivity per unit area and time, mitigates total crop loss, and promotes biodiversity. It also improves water use efficiency by 20–25% and enhances nutrient use efficiency by 25–30%. Additionally, legume intercropping reduces yield losses from pests and diseases by 20–25% compared to sole cropping systems. The practice bolsters crop resilience through ecological processes like bio-littering, bio-ploughing, bio-irrigation, and bio-pumping (the "4Bs"), which are valuable for adapting to climate variability. However, research gaps remain, particularly in the optimal selection of legume species for specific regions, suitable agronomic practice for each system, and addressing socio-economic barriers to widespread adoption.

KEYWORDS

intercropping, nutrient cycling, resource utilization, climate resilience, pulses



GRAPHICAL ABSTRACT

1 Introduction

The Food and Agriculture Organization (FAO) estimates that by 2050, food production must grow by 70% from 2005 to feed a population of 9.7 billion (Falcon et al., 2022). The modern input-intensive monoculture has boosted food production and self-sufficiency (Belete and Yadete, 2023) but it relies heavily on synthetic fertilizers and pesticides, leading to declining soil health, groundwater depletion, pest and disease outbreaks, environmental problems like eutrophication, greenhouse gas (GHG) emissions, and biodiversity loss (Mrabet, 2023; Ahmed et al., 2022). These challenges, compounded by increasing climate vulnerability, further threaten sustainability. Therefore, sustainable farming strategies are critically needed to increase food production while minimizing environmental harm.

In response to these challenges, researchers and practitioners are advocating for a transition to more resilient and efficient cropping systems that ensure long-term food security without harming the ecosystem (Glaze-Corcoran et al., 2020). Crop diversification, through the introduction of various crops in temporal and spatial arrangements, has emerged as a promising strategy for enhancing agroecosystem health and sustainability (Stomph et al., 2020). Cover crops are plants grown between main crops to improve soil health and protect the land from soil erosion during the off-season. These crops are not harvested for profit. Crop rotation is the practice of planting different crops in the same field in successive growing seasons. Intercropping is the cultivation of more than one crop simultaneously on the same piece of land with a defined row pattern. Intercrops provide benefits like additional income and insurance against total crop failure. Agroforestry is a land-use management system that combines agricultural crops with trees and shrubs.

Practices like cover cropping, crop rotation, intercropping, and agroforestry significantly improve ecosystem services, such as enhancing soil fertility, increasing water infiltration, reducing erosion, sequestering carbon, and supporting biodiversity (Barman et al., 2022). These practices also conserve soil moisture, reduce synthetic nitrogen (N) fertilizer requirements, lower fossil energy consumption, and suppress weeds and pests (Duchene et al., 2017; Bybee-Finley and Ryan, 2018; Stomph et al., 2020). All these benefits are derived mainly by incorporating legumes in cropping systems. Among crop diversification methods, legume intercropping has garnered significant attention due to its numerous ecological and economic advantages. Legume symbiosis with rhizobial bacteria converts atmospheric nitrogen (N_2) into plant-available forms such as ammonium (NH_4^+) and nitrate (NO_3^-), enriching soil N levels and reducing the need for external N inputs (Bybee-Finley and Ryan, 2018). This natural process lowers the environmental impact of agriculture and enhances soil fertility besides promoting sustainability (Stagnari et al., 2017). In addition to N fixation, legumes contribute to improving soil health through various mechanisms. These mechanisms are classified into four 'B's *viz.,* bio-littering, bio-ploughing, bio-irrigation, and bio-pumping (Delaquis et al., 2018).

Bio-littering refers to the accumulation of organic residues like leaves and stems on the soil surface. As these residues gradually decompose, they enrich the soil with nutrients and organic matter, thereby improving its fertility. Bio-ploughing occurs when deep-rooted

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plants loosen and aerate compacted soil layers, enhancing root penetration and water infiltration. Similarly, bio-irrigation improves soil water availability by facilitating water movement, ensuring optimal moisture distribution in the soil. Finally, bio-pumping allows deep-rooted plants to draw nutrients and water from the subsoil, redistributing them to the topsoil to benefit companion crops. While the benefits of legume intercropping are well-documented, its adoption remains limited in many regions due to a range of technical, socio-economic, and policy-related challenges (Delaquis et al., 2018).

Overcoming these barriers requires a multifaceted approach that includes improving farmer access to knowledge, resources, and support systems. Providing region-specific guidance on legume intercropping techniques, tailored to local soil and environmental conditions, can help maximize its effectiveness. Additionally, fostering collaboration between researchers, policymakers, and farmers can address socio-economic and policy constraints, creating an enabling environment for wider adoption (Kumawat et al., 2022). This review evaluates the role of legume intercropping in improving soil health, resource use efficiency, and crop productivity across diverse agro-ecological conditions, positioning legume intercropping as a "win-win solution" to address the challenges of food security, environmental sustainability, and climate change. It also explores optimal crop combinations and socio-economic barriers to its broader adoption and recommends suitable interventions to overcome existing barriers.

2 Selection of literature

For this review, 511 research articles and book chapters on legume intercropping were gathered from the Web of Science using keywords such as intercropping, N fixation, nutrient cycling, resource utilization, soil conservation, and climate change resilience. Articles unrelated to climate change resilience, those lacking a focus on N fixation, and certain book chapters were excluded, reducing the pool to 300. A detailed examination of 240 articles followed, specifically focusing on biological nitrogen fixation (BNF) and its role in environmental stability and sustainability. Figure 1 presents the PRISMA flow chart illustrating the systematic review process.

3 Improving resource use efficiency through legume intercropping

Legume intercropping enhances climate resilience by improving resource efficiency and natural suppression of pests, pathogens, and weeds, which in turn boost farm profitability despite increased management complexity and labor needs (Stomph et al., 2020). Intercrops occupy different spatial niches and achieve higher combined productivity than monocultures, resulting in greater yield and economics per unit area (Ahmed et al., 2022). Efficient intercrops often have complementary solar radiation needs, for example, shade-tolerant plants thrive beneath shade-intolerant crops, optimizing space (Sahoo et al., 2023). Intercropping maize and peanuts helps to augment the yield up to 44% more than their respective monocultures. Maize initially outcompetes peanuts, but peanuts recover yield potential after maize harvest. Plants with different root structures utilize various soil layers for nutrients and water, reducing weed pressure and management needs and further decreasing land requirements

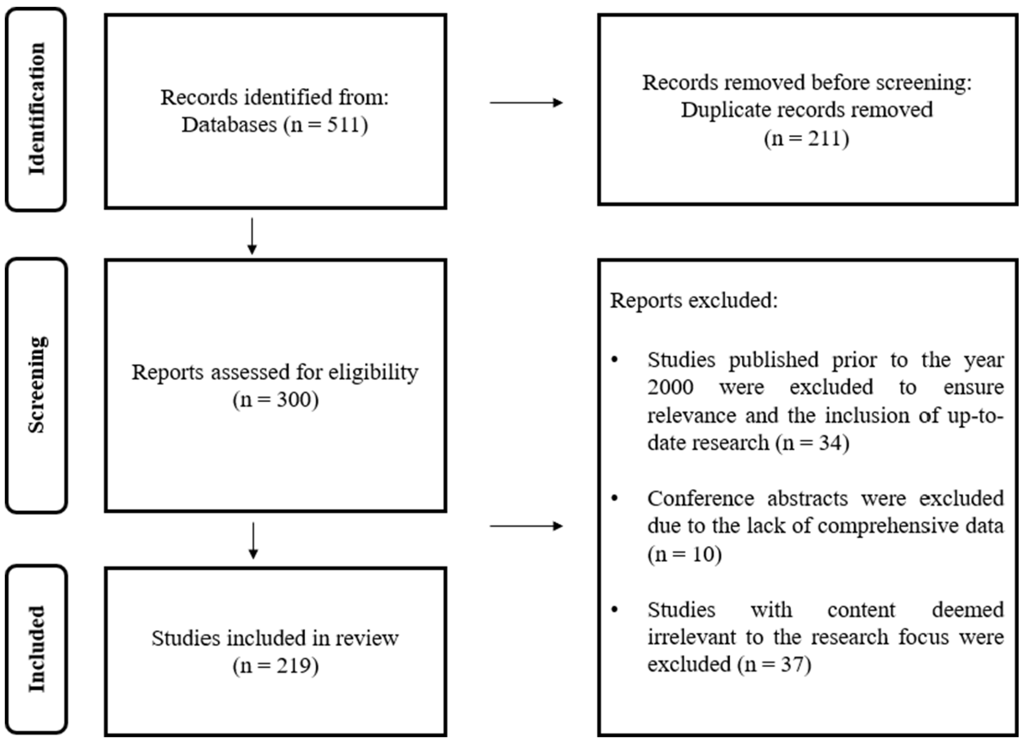

FIGURE 1
PRISMA flow chart for a systematic review process.

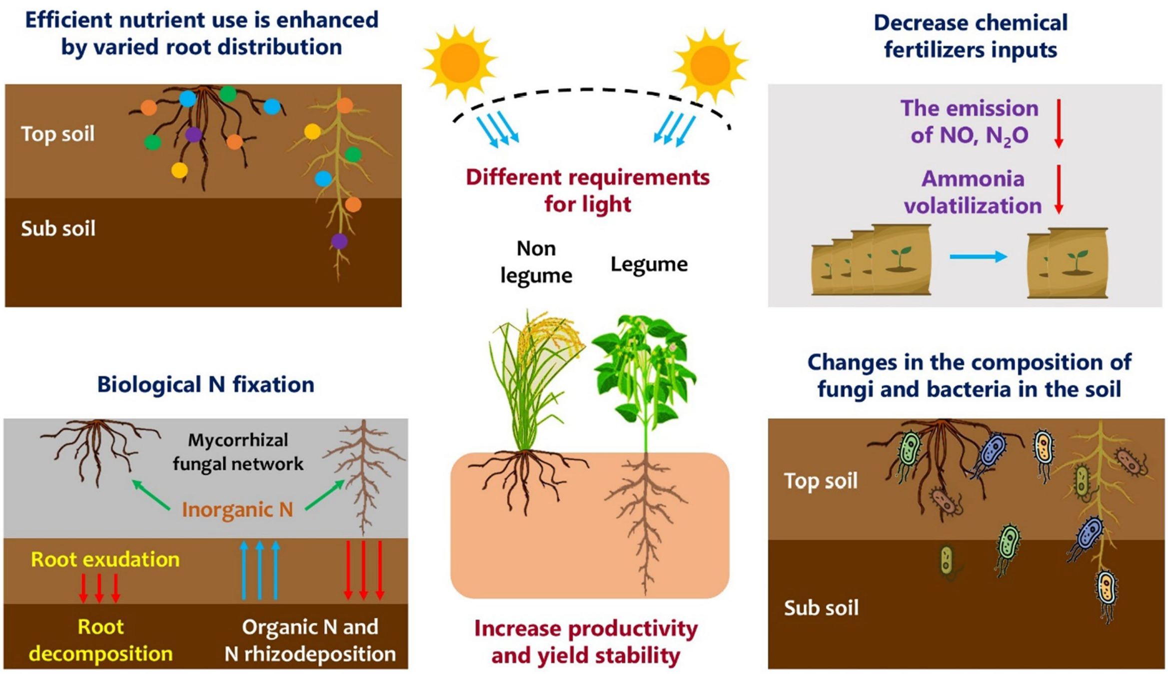

FIGURE 2
Legume intercropping boosts resource use efficiency by enhancing interspecific facilitation and niche differentiation (adapted from Yang et al., 2021).

compared to separate monocultures at similar densities (Temesgen et al., 2016). Figure 2 illustrates how legume intercropping enhances resource use efficiency by promoting interspecific facilitation and niche differentiation.

3.1 Pest and pathogen suppression

Intercropping typically reduces pest pressure compared to monocultures by hindering pests ability to locate a host plant. Intercrops obstruct pest foraging, camouflage crops, and mask plant odors, making it harder for pests to find targets. For example, when peas and wheat were intercropped, the visual consistency of the wheat field was broken by the contrasting leaves of peas. The pests like wheat aphids found it more difficult to find and target the wheat as a result of this visual disturbance (Aziz et al., 2015). Aerial pests are more likely to land on unsuitable plants in diverse intercrops, reducing their search efficiency and increasing the likelihood of predation before finding a suitable host (Mir et al., 2022). When maize is intercropped with *Desmodium* and napier grass is planted around the field, it repels maize stem borer (*Busseola fusca*). The stemborer moths often land on the *Desmodium* plants, which are unsuitable hosts, thereby delaying their search for maize plants. This delay increases their exposure to natural predators (Rahman, 2021). Similarly, perennial peanuts and coriander lower whitefly populations and reduce yellow mottle virus in tomato crops.

Intercropping reduces disease incidence by altering microclimates, suppressing virus vectors, diluting host plant pools, and fostering plant–soil feedbacks that inhibit them (Huss et al., 2022). For example, living mulches like buckwheat or white clover between squash rows enhance natural enemies and reduce aphid and whitefly colonization, limiting pathogen spread (Razze et al., 2016). Meta-analyses by Li et al. (2023) showed that legume/grain intercropping reduces pathogen incidence by 34%. Besides harboring pathogens, oilseed/legume intercrops also suppress soil fungi, nematodes, and weeds through allelopathy. Allelopathic chemicals produced by legumes, such as phenolic acids and flavonoids, suppress weed germination and growth. Groundnut (*Arachis hypogaea*) residues have been shown to reduce weed density in intercropping systems by releasing phenolic compounds, including p-coumaric acid, ferulic acid, and caffeic acid, into the soil (Prasad et al., 2020).

A meta-analysis by Chadfield et al. (2022) revealed that intercropping reduces plant-parasitic nematode damage by 40% and disease incidence by 55% by influencing factors like fertilization and crop family. Despite yield reductions from intercrop competition, nematode control offset losses, making intercropping a viable strategy. By enhancing system resilience against biotic stresses, intercropping reduces yield losses by 40–55%, providing significant benefits for sustainable agriculture. This approach enhances biodiversity by supporting beneficial insects, birds, and soil organisms, which boosts ecosystem services and farming sustainability (Duru et al., 2015). Intercropping cowpea with cotton lowers sucking pests, and groundnut with upland rice minimizes stem borers (*Chilo zacconius*) and green stink bugs (*Nezara viridula*). Intercropping peanuts with beans cuts pest incidence of cotton jassid by 30 to 50%, and in soybean-maize intercropping, the incidence of *Spodoptera* in maize is reduced from 15 to 35% (Pierre et al., 2023). Table 1 displays the impact of intercropping on pest and disease control with associated yield increments.

TABLE 1 Impact of legume intercropping on pest and disease control with associated yield increments.

Primary crop	Intercrop	Pest/Disease controlled	Method of control	Yield gain (%)	References
Maize	Beans	Fall armyworm (P)	Disruption of pest movement	17%	Midega et al. (2018)
Groundnut	Sorghum	*Aphis craccivora* (P)	Natural pest repellence	13%	Balikai et al. (2020)
Cassava	Maize	Cassava mosaic virus (D)	Reduced virus spread due to mixed canopy	14%	Houngue et al. (2019)
Sunflower	Soybean	Sunflower helianthus rust (D)	Diversion of disease to non-economic plant	16%	Soto et al. (2020)
Wheat	Clover	Wheat aphid (P)	Biodiversity increases natural enemies	20%	Storkey et al. (2019)
Pearl millet	Groundnut	Downy mildew (D)	Improved air circulation reducing humidity	22%	Thakur et al. (2011)
Pea	Barley	Powdery mildew (D)	Physical barrier and habitat modification	14%	Devi et al. (2022)
Maize	Cowpea	Stem borer (P)	Disruption of pest habitat	15%	Mutyambai et al. (2022)
Cotton	Groundnut	Bollworm (P)	Groundnut attracts natural predators	25%	Rajendran et al. (2018)

P, Pest; D, Disease.

3.2 Improving water use efficiency

Incorporating legumes with cereals has been shown to enhance water use efficiency (WUE) by 25% over monocultures by optimizing water uptake and reducing soil evaporation, particularly during drought conditions (Fernández-Ortega et al., 2023). Mupangwa et al. (2021) demonstrated a 25% improvement in WUE in maize-groundnut intercropping systems compared to monoculture maize. This enhancement was attributed to the groundnut's shallow rooting pattern, which effectively utilized surface moisture, minimizing competition for subsoil water required by maize. Similarly, Dai et al. (2019) highlighted the benefits of sorghum-cowpea intercropping, where cowpea roots predominantly exploited surface moisture, allowing sorghum to access deeper soil water reserves. This complementary root system facilitated efficient water partitioning and significantly reduced competition between the crops. Venkatesh et al. (2010) reported that lucerne intercropped with maize lifted significant quantities of water from deeper soil horizons, which was subsequently utilized by maize during periods of limited rainfall.

Pulse crops, such as chickpeas and lentils in northern and central India, and mung bean, urd bean, cowpea, and lentil in southern, eastern, and northeastern India, are highly water-efficient. These crops thrive on residual soil moisture and typically require less irrigation than rice, which needs 5–6 irrigations in the same period (Kumar, 2023). Due to their distinct morphology and physiology, pulses not only have a lower water demand but also demonstrate a higher WUE compared to cereals and oilseeds. Additionally, deep-rooted legumes like lucerne and clovers effectively mitigate waterlogging by extracting moisture from deeper soil layers (Jordan, 2022). Among all pulses, dry peas exhibited the highest WUE (8.3 kg ha^{-1} mm^{-1}), whereas chickpeas showed the lower WUE (5.62 kg ha^{-1} mm^{-1}) (Wang et al., 2012). This hydraulic lift mechanism of legumes, where deep-rooted plants like legumes redistribute water from deeper soil layers to drier topsoil at night, and nutrient-efficient intercropping, underscores the potential of leguminous systems to improve resource efficiency, optimize water use, and enhance crop performance, particularly in low-input and rainfed agriculture. The impact of legume intercropping on improving resource use efficiency is summarized in Table 2.

3.3 The four 'B's concept for leguminous crops

The concept of the four 'B's *viz.*, bio-littering, bio-ploughing, bio-irrigation, and bio-pumping provides an innovative framework for understanding the benefits of leguminous crops in sustainable agriculture. Legumes, offer multiple harvests, improve soil fertility, and enhance nutrient and moisture levels in the soil. Known for their high drought tolerance and biomass productivity, these crops serve as an excellent source of fodder and soil enrichers, thereby supporting soil health and promoting sustainable farming practices amid climate variability and drought conditions (Chitraputhirapillai et al., 2022). Figure 3 demonstrates the four 'B's concept, illustrating how leguminous crops enhance resource use efficiency.

Among these practices, bio-ploughing is an effective soil structure improvement technique in which the deep-rooting abilities of leguminous crops such as pigeon pea (*Cajanus cajan*) and cowpea (*Vigna unguiculata*) alleviate the problem of soil compaction (Chitraputhirapillai et al., 2022). By penetrating compacted soil layers, these crops create micropores that enhance water infiltration and improve soil structure (Dugassa, 2023). Bio-ploughing not only loosens the soil but also reduces soil erosion by increasing infiltration rates (Priori et al., 2020). Additionally, intercropping leguminous crops like

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TABLE 2 The influence of legume intercropping on improving resource use efficiency.

Intercropping	WUE under monocropping (%)	WUE undue intercropping (%)	NUE under monocropping (%)	NUE under intercropping (%)	Bio-ploughing	Bio-littering	Bio-irrigation	Bio-pumping	% yield over monocropping	References
Maize + Cowpea	15.4%	20%	20%	25%	Enhances root penetration	Increases OM	Improves water infiltration	Recycles deep N	30%	Tamta et al. (2019)
Wheat + Chickpea	18.7%	22%	22%	28%	Loosens compact soil	Boosts soil fertility	Reduces evaporation	Makes P bioavailable	32%	Betencourt et al. (2012)
Sorghum + Pigeon pea	20%	25%	25%	30%	Breaks up soil compaction	Adds N-rich litter	Deep roots enhance water retention	Accesses deep nutrients	35%	Phiri and Njira (2023)
Barley + Lentil	16.0%	18%	20%	22%	Improves aeration of soil	Improves SOC	Reduces water stress	Pumps up micronutrients	28%	Tosti et al. (2023)
Rice + Mung bean	18.2%	23%	24%	29%	Enhances water percolation	Increases litterfall	Conserves soil moisture	Improves K availability	33%	Li et al. (2009)
Cotton + Groundnut	19.1%	24%	22%	26%	Enhances soil tilth	Recycles crop residue nutrients	Enhances capillary rise of water	Mobilizes P and zinc	34%	Reddy and Mohammad (2009)
Pearl millet + Cowpea	21.5%	27%	25%	30%	Facilitates soil aeration	Improves nutrient cycling	Improves water availability	Increases N uptake	36%	Indoria et al. (2016)
Sugarcane + Soybean	20.7%	25%	23%	28%	Enhances subsoil porosity	Adds OM	Reduces water loss	Brings up micronutrients	35%	Singh (2008)
Maize + Groundnut	17.0%	22%	21.0%	27%	Enhances nutrient mobility	Adds N and carbon to soil	Prevents erosion	Pumps deep minerals like Mg and P	31%	Mubarak et al. (2002)
Wheat + Pea	16.7%	20%	19%	23%	Breaks hardpan	Contributes to N build-up	Retains soil moisture	Increases nutrient availability	30%	Rathi et al. (2024)
Finger millet + Cowpea	18.0%	24%	23%	29%	Increases root penetration	Enhances nutrient recycling	Promotes water storage	Enhances P and K	33%	Peter et al. (2024)
Sunflower + Chickpea	16.0%	21%	20%	26%	Increases soil porosity	Adds organic residues	Retains water in dry periods	Pumps essential nutrients	34%	Shatkovskyi et al. (2022)
Maize + Soybean	19.3%	26%	22%	28%	Loosens soil	Returns high N litter	Improves soil moisture	Mobilizes deep soil N	35%	Ning et al. (2022)
Sorghum + Groundnut	16.6%	22%	23%	30%	Reduces soil compaction	Recycles OM	Reduces water requirements	Pumps P from deeper layers	33%	Mohanty et al. (2024)
Barley + Faba bean	18.5%	23%	22%	28%	Enhances root depth	Improves N availability	Enhances water retention	Pumps up nutrients	32%	Fouda et al. (2022)

(Continued)

TABLE 2 (Continued)

Intercropping	WUE under monocropping (%)	WUE undue intercropping (%)	NUE under monocropping (%)	NUE under intercropping (%)	Bio-ploughing	Bio-littering	Bio-irrigation	Bio-pumping	% yield over monocropping	References
Rice + Soybean	17.9%	24%	21%	27%	Improves soil structure	Adds OM	Improves water percolation	Brings nutrients to surface	34%	Suntoro et al. (2020)
Cotton + Mung bean	18.5%	25%	23%	30%	Increases subsoil aeration	Residue and nutrient recycling	Retains moisture	Mobilizes deep nutrients	35%	Liang et al. (2020)
Wheat + Lupin	16.2%	20%	19%	24%	Increases soil pore space	Increases N reserves	Reduces drought stress	Pumps deep nutrients	31%	Lalotra et al. (2022)
Maize + Lentil	17.0%	23%	22%	29%	Improves root penetration	Returns high N residues	Improves moisture retention	Enhances micronutrient availability	36%	Venkatesh et al. (2014)
Finger millet + Groundnut	19.4%	26%	23%	30%	Increases subsoil fertility	Recycles crop litter	Increases soil water retention	Pumps N and K	34%	Ramachandra et al. (2023)

N, Nitrogen; P, Phosphorus; K, Potassium; WUE, Water use efficiency; NUE, Nutrient use efficiency; OM, Organic matter; SOC, Soil organic carbon.

faba bean (*Vicia faba*), clover (*Trifolium* spp.), and pigeon pea (*Cajanus cajan*) with mustard (*Brassica* spp.), rye (*Secale cereale*), and oats (*Avena sativa*) and organic amendments addition has shown to increase soil health and resilience by approximately 35% (Raihan, 2023). This approach reduces the need for mechanical tillage, which in turn lowers fuel consumption and GHG emissions while also supporting sustained improvements in soil organic carbon (SOC) and microbial biomass over multiple cropping seasons (Kumar, 2023). Therefore, bio-ploughing offers a sustainable alternative to conventional soil management methods by enhancing soil structure, water infiltration, and overall agricultural sustainability under legume intercrop systems.

Bio-littering, another beneficial practice, enhances soil health and agricultural productivity by providing a renewable source of organic matter (OM) and nutrients, thereby reducing the reliance on synthetic fertilizers (Mugi-Ngenga et al., 2022). This practice supports sustainable agriculture by fostering soil fertility, promoting environmental sustainability, enhancing nutrient cycling, and reducing GHG emissions (Tahat et al., 2020). Bio-littering of legumes adds OM to the soil through leaf litter and root residues, which increases SOC and N levels and supports higher yields for subsequent non-leguminous crops in rotational systems. Moreover, legume crop litter significantly contributes to nutrient levels in the soil. For instance, Hu et al. (2023) reported that alfalfa (*Medicago sativa*) litter supplies approximately 35 kg N ha^{-1}, while Jensen et al. (2020) reported a N contribution of up to 85 kg ha^{-1} from faba bean (*Vicia faba*) and clover (*Trifolium* spp.) litter. In total, N from legume litter, stems, and seeds can reach up to 150 kg ha^{-1}, with about 30% of this N returned to the soil (Wang J. et al., 2024).

Pulse crop residues supply between 20 and 80 kg N ha^{-1}, accounting for around 70% of biologically fixed N, depending on the crop and environmental conditions (Lal, 2017). Sequential cropping systems with a preceding pulse crop can add between 18 to 70 kg N ha^{-1} to the soil, reducing fertilizer needs by 25–30% (Kaur and Singh, 2022). Specifically, faba beans and lentils contribute around 39 kg N ha^{-1} and 40 kg N ha^{-1}, respectively, through their residues, further improving soil fertility (Lalotra et al., 2022). Intercropping legumes such as chickpeas with cereals like durum wheat has been shown to lower soil pH, enhancing phosphorus (P) solubility and availability (Sharma et al., 2023). Studies have reported a 28.5% increase in available P in the rhizosphere of intercropped systems compared to monocultures (Souid et al., 2024). Additionally, intercropping legumes with cereals is associated with higher biomass production and improved grain yields.

Bio-irrigation and pumping, facilitated by the hydraulic lift mechanism in deep-rooted leguminous crops, offer additional benefits in intercropping systems, particularly in semi-arid or rainfed conditions. The hydraulic lift can provide an additional 25–40 mm of water to the topsoil during dry periods, benefiting shallow-rooted companion crops in intercrop systems (Caldwell and Richards, 1989; Fenta et al., 2022; Kumar and Boraiah, 2022). A study conducted on hydraulic lift in *Cullen pallidum* and *Medicago sativa* showed an improvement in water availability and survival of interplanted *Trifolium subterraneum* under dry topsoil conditions. *T. subterraneum* maintained similar or slower declines in leaf water potential compared to well-watered plants, depending on the interplanted species. Despite alleviated water stress, nutrient uptake in *T. subterraneum* was not enhanced by hydraulic lift (Pang et al., 2013). Research indicates that alfalfa's hydraulic lift can increase upper soil moisture by up to 15% (Wang Y. et al., 2024), while deep-rooted legumes can boost water

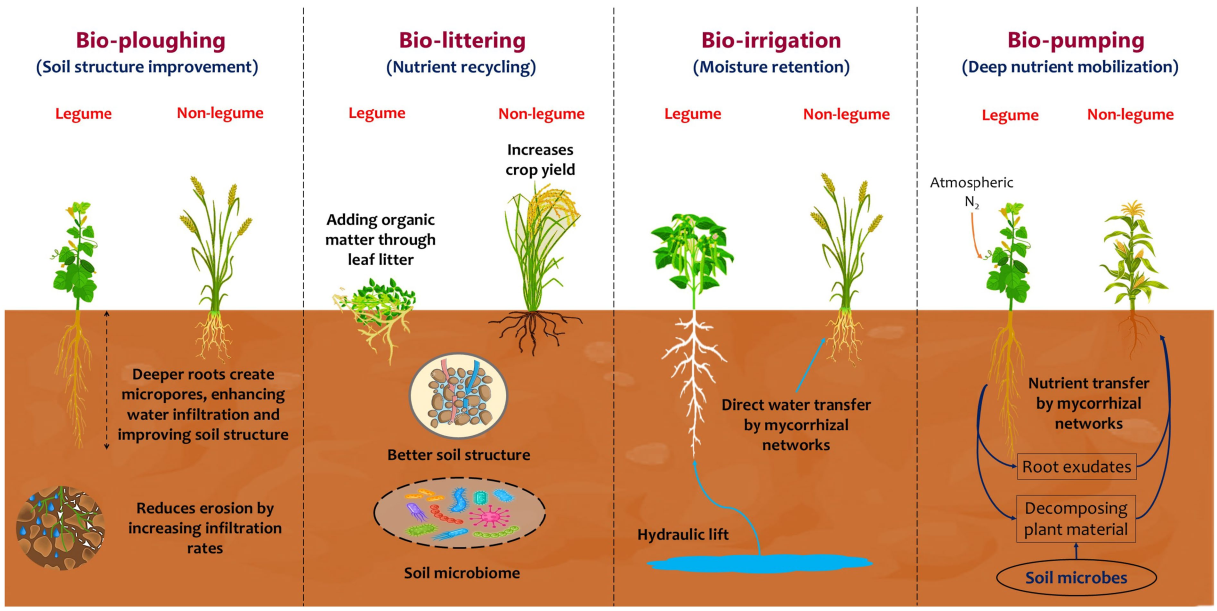

FIGURE 3
The four 'B's concept for leguminous crops in enhancing resource use efficiency.

availability for neighboring finger millet by approximately 20% (Singh et al., 2020).

4 Nitrogen fixation through legume intercropping

Nitrogen is vital for plant growth and productivity, with most research focusing on BNF in grain legumes, as they obtain up to 75% of their N needs from atmospheric sources (Zhao et al., 2022). Cereal + legume intercropping systems often enhance nutrient dynamics by improving N uptake and overall nutrient status. In these systems, legumes fix atmospheric N_2, which benefits nearby cereal crops through mechanisms like root interactions, root exudation, and mycorrhizal associations, ultimately increasing N efficiency (Lan et al., 2023). By fixing atmospheric N_2, legumes contribute to soil N replenishment and nutrient recycling, thriving under low inputs and adverse conditions (Kebede, 2021). For example, wheat + soybean, maize + faba bean, barley + pea, and sorghum + soybean intercropping systems show significant N acquisition improvements compared to sole cropping. Faba bean + maize intercropping showed a 72% increase in N acquisition, underscoring its efficiency in N assimilation (Zhao et al., 2022).

Globally, BNF in cereal-based cropping systems contributes around 50 teragram (Tg) of annual N fixation, with 34.4 Tg originating from grain legumes and 15.6 Tg from non-symbiotic sources (de Moissac, 2020). Legume intercropping systems are valuable for soil fertility, fixing around 150 tons of atmospheric N_2 annually and enhancing soil conservation through increased ground cover compared to monocultures (Ananthi and Parasuraman, 2021). BNF converts atmospheric N_2 into ammonia (NH_3) with the help of rhizobia, meeting up to 80% of the legume N needs (Guo K. et al., 2023) and reducing synthetic N inputs by 70–90%, thereby promoting sustainable agriculture (Ladha et al., 2022). This process also enhances soil N retention in maize-legume intercropping systems and reduces N leaching by 30% (Gardarin et al., 2022). Similarly, in pulse-wheat rotations, pulses supply 20–40% of the N needed by wheat, showcasing their role in improving N cycling and soil fertility, though the exact N transfer remains challenging to quantify (Tripathi et al., 2021). Overall, BNF not only reduces the reliance on chemical N inputs but also enhances fertilizer efficiency and mitigates environmental impacts. These systems also contribute to reducing nitrate leaching by 10–16% compared to monocultures (Hauggaard-Nielsen et al., 2009).

Research utilizing techniques like 15 N labeling has illustrated the direct transfer of N from legumes to neighboring cereals, through root exudation, where nitrogenous compounds like amino acids are released into the soil. Additionally, rhizodeposition of decayed root nodules, and shared mycorrhizal networks facilitate nutrient exchange, enhancing overall N uptake and boosting yield (Raza et al., 2023). However, the spatial arrangement is crucial, as excessive distance between legumes and non-legumes can hinder N transfer. Many findings signified that N competition in legume-cereal mixtures may intensify due to the N-fixing activity of legumes (Kebede, 2021). The effectiveness of legume intercropping depends on factors such as species selection, crop morphology, plant density, cultivation practices, and N-fixing capacity. Legumes adjust the carbon-nitrogen (C:N) ratio and boost soil enzyme activity, which enhances nutrient conversion efficiency. Key legume crops like soybean, common bean, cowpea, lablab, and groundnuts play crucial roles in BNF. Soybeans, for example, can meet 50–60% of their N needs through BNF, highlighting their importance in sustainable N management (Lai et al., 2022).

The symbiotic relationship between legumes and rhizobia is crucial for BNF, a process in which rhizobia infects legume roots to form nodules where N fixation occurs. Well-nodulated legumes can fix over 250 kg N ha^{-1} $year^{-1}$, significantly enhancing plant growth and soil fertility (Fahde et al., 2023). Under optimal conditions, N fixation rates can reach up to 300 kg N ha^{-1} $year^{-1}$ (Zhang et al., 2021). The efficiency of N fixation varies among the different species, wherein soybean fixes between 60 and 300 kg N ha^{-1} $year^{-1}$, while crops like alfalfa and clover can fix as much as 150–500 kg N ha^{-1} year. Factors such as soil pH, texture, and OM content have a significant impact on the efficiency of BNF (Issah et al., 2020). Soil pH significantly influences N fixation efficiency in legumes. Soybean had optimal nodulation and N fixation in slightly acidic to neutral soils (pH 6.0–7.0) (Nakei et al., 2023). Similarly, mung beans (pH 6.0–6.5) and alfalfa (pH 6.5–7.5) performed best in slightly acidic to neutral soils, indicating the importance of maintaining optimal soil pH for maximizing BNF.

For example, in a study comparing *Dolichos lablab* + maize (LM), fodder soybean + maize (FM), and maize monoculture (M), the application of 240 kg N ha^{-1} to the *Dolichos lablab* + maize system increased dry biomass yield and forage quality, achieving a nitrogen use efficiency (NUE) of 59.5% (Zhang et al., 2022). Additionally, maize + legume intercropping saved 25% of N (37.5 kg ha^{-1}) needed for the subsequent wheat crops, indicating that this strategy could improve soil N fertilizer usage and reduce reliance on synthetic N fertilizers by approximately 26% (Nasar et al., 2023). Crops like pigeon pea and chickpea, when intercropped with cereals such as sorghum or maize, can increase soil fertility and N fixation by 30–50% (Chamkhi et al., 2022). These intercropping systems not only boost soil N levels but also enhance microbial diversity in the rhizosphere, supporting nutrient cycling and overall soil health (Solomon et al., 2023). Table 3 represents the pulse intercropping on N fixation in different crops.

Furthermore, excess N fertilizer application poses environmental risks, contributing to nitrate contamination in groundwater and nitrous oxide emissions. Legume intercropping can mitigate these issues by enhancing resource use efficiency, reducing ammonia volatilization, and lowering nitrous oxide emissions (Hassan et al., 2022). In cereal-legume systems, the competitive N uptake by cereals prompts legumes to fix more atmospheric N_2, indirectly reducing the reliance on synthetic fertilizers, thereby decreasing environmental pollution and nitrate concentrations in the soil and surrounding ecosystems (Grzebisz et al., 2022). Shifting a portion of global cereal cropland to cereal-legume intercropping systems could potentially lower N fertilizer use by 26%, significantly reducing agriculture's carbon footprint.

TABLE 3 Pulse intercropping on N fixation in different crops.

Primary crop	Legume crop	N fixation (kg^{-1} ha^{-1} $year^{-1}$)	References
Maize	Common bean	50–150	Nassary et al. (2020)
Maize, Sorghum	Soybean	100–200	Nakei et al. (2023)
Millet, Sorghum	Cowpea	50–200	Nair et al. (2018)
Maize, Millet	Pigeon pea	50–300	Lavanya et al. (2019)
Wheat	Chickpea	60–120	Koul et al. (2022)
Barley, Wheat	Lentil	50–150	Singh et al. (2022)
Barley, Oats	Pea	70–150	Baxevanos et al. (2017)
Wheat, Barley	Faba bean	150–300	Stagnari et al. (2017)
Rice	Mung bean	50–100	Mutti et al. (2019)
Wheat, Barley	Lupin	100–200	Schreuder (2021)

4.1 Nutrient improvement of legume intercropping beyond nitrogen and phosphorus

Legume intercropping is renowned for enhancing N and P availability via BNF and improved P solubility. Beyond these, it also benefits the cycling and availability of essential macro- and micronutrients such as potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn), iron (Fe), and boron (B) through root exudation, microbial activity, and enhanced soil organic matter. These nutrients are vital for plant growth, productivity, and soil health, making legume intercropping an effective tool for addressing nutrient deficiencies. Intercropping legumes with cereals enhances K availability through root exudation of organic acids, releasing K from non-exchangeable reserves. Maize + legume intercropping has shown a 15–20% increase in soil exchangeable K compared to monocropping (Wang et al., 2014). Deep-rooting legumes like pigeon pea access subsoil K and recycle them to the topsoil through leaf litter and root turnover. Maize + soybean intercropping enhances K uptake and nutrient accumulation in roots and green biomass by 20% with optimal K application (80:60 kg ha^{-1}) compared to no K application (Ahmed et al., 2020). In soybean-based systems, K uptake primarily occurs from shallow soil layers, while intercropping improves K cycling and efficiency (Maciel de Oliveira et al., 2020). Additionally, legumes like alfalfa excrete organic acids that mobilize less-available K forms, benefiting both intercrop species (Gao et al., 2022). This reduces reliance on K fertilizers, especially in K-deficient soils.

Legume intercropping also improves Ca and Mg availability, essential for cell wall stability, enzymatic functions, and photosynthesis. Ca-rich leaf litter from legumes like cowpea and groundnut enriches soil Ca upon decomposition, benefiting associated crops like maize and millet. Legume root exudates solubilize Mg from soil minerals, improving its availability (Sardans et al., 2023). Furthermore, legume intercropping enhances micronutrient bioavailability, such as Zn, Fe, and B, through rhizosphere interactions and microbial activity, promoting enzymatic functions and stress resistance. For example, chickpea + maize intercropping systems increased soil Zn availability by 25% due to microbial solubilization (Kumar et al., 2022). Legume roots release organic acids and phytosiderophores, chelating Zn and making it more accessible to companion crops. Similarly, wheat + lentil intercropping increased Fe uptake by 30%, facilitated by root exudates and microbial siderophores (Siddiqui et al., 2021), benefiting high-pH soils. Additionally, peanut + sorghum systems showed a 15% increase in soil B availability, boosting sorghum grain quality and yield through root-mediated organic compound release (Patel et al., 2019). Targeted management strategies can optimize these benefits, promoting sustainable agriculture while enhancing soil health and ecosystem resilience.

5 Soil response to legume intercropping

Soil nutrient content is a very good indicator of soil fertility, with crop yield serving as a direct measure of soil health. Legume intercropping has emerged as one of the key strategies for sustainable intensification, providing greater stability in soil fertility and environmental health compared to sole cropping systems. Low soil fertility can limit crop production, but incorporating legumes into cropping systems has been shown to improve soil's physical, chemical, and biological properties by fixing atmospheric N_2, leaf shedding, and mobilizing insoluble nutrients, which in turn enhances nutrient availability and use efficiency (Table 4). Over a five-year study, Tang et al. (2021) found that intercropping legumes with cereals increased soil OM by 20%, total N by 15%, and available P by 10%, indicating enhanced soil fertility and nutrient availability. Figure 4 illustrates the physiological mechanisms driving interspecific facilitation in the acquisition of N, P, and water in intercropping systems.

5.1 Physical properties

Legumes play a significant role in enhancing soil physical properties, including bulk density, saturated hydraulic conductivity, and the stability of cracking clay. Legume intercropping systems increase the proportion of macro- and micro-aggregates by 52 and 111%, respectively, compared to sole crops (Garland et al., 2017). This structural improvement helps to reduce soil erosion. For example,

TABLE 4 Impact of legume intercropping on soil physical, chemical, and biological properties.

Intercropping system	Soil physical properties	Soil chemical properties	Soil biological properties	References
Finger millet + Groundnut	Increased water retention	35% higher N content	Increased AMF colonization	Srinivasarao et al. (2012)
Sorghum + Pigeon pea	Enhanced soil aggregation	Boosted soil N by 40%	Increased microbial biomass carbon (MBC)	Weldeslassie et al. (2016)
Pearl millet + Cowpea	Improved infiltration rates	Boosted soil N by 38%	Enhanced rhizosphere microbial activity	Siébou et al. (2019)
Maize + Cowpea	Increased soil porosity and root penetration	Increased soil N by 35%	Increased rhizobia population for N fixation	Eze et al. (2020)
Barley + Lentil	Better moisture retention	Increased cation exchange capacity (CEC)	Improved N-fixing bacteria	Rajpoot et al. (2020)
Cotton + Groundnut	Improved capillary rise of water	30% increase in organic matter	Increased beneficial nematode populations	Chi et al. (2019)
Wheat + Chickpea	Reduced compaction	30% increase in soil organic carbon (SOC)	Increased enzyme activity for nutrient cycling	Mbanyele et al. (2024)
Sugarcane + Soybean	Reduced soil crusting	Balanced pH levels	Enhanced microbial biomass nitrogen (MBN)	Morsy et al. (2017)
Barley + Faba bean	Increased root penetration	31% increase in N content	Enhanced microbial community structure	Dordas et al. (2019)
Wheat + Pea	Reduced soil compaction	28% increase in soil N	Increased fungal diversity	Longepierre et al. (2022)
Rice + Mung bean	Reduced soil erosion	Improved soil pH balance	Enhanced root exudates promoting microbial growth	Papong and Cagasan (2020)
Finger millet + Cowpea	Increased porosity	34% higher N content	Increased beneficial fungi	Peter et al. (2024)
Maize + Groundnut	Reduced bulk density	Improved N (36%) availability	Higher rhizobia populations	Ajayi (2015)
Sunflower + Chickpea	Enhanced water infiltration	Increased N by 32%	Increased enzymatic activity	Ullah et al. (2018)
Sorghum + Groundnut	Enhanced moisture retention	Increased N by 39%	Increased AMF colonization	Watts-Williams et al. (2022)
Maize + Soybean	Better root structure	Boosted N and SOC levels	Increased microbial biomass	Bawa et al. (2019)
Cotton + Mung bean	Enhanced root proliferation	33% increase in soil N	Increased rhizobia activity	Ali et al. (2020)
Rice + Soybean	Increased soil aggregation	Increased N and P levels	Increased root-associated microbes	Nascente and Stone (2018)
Maize + Lentil	Enhanced root penetration	Increased N by 38%	Increased fungal and bacterial diversity	Razavi et al. (2016)
Wheat + Lupin	Increased porosity	Increased soil N (27%)	Increased enzyme activities	Esnarriaga et al. (2020)

N, Nitrogen; P, Phosphorus.

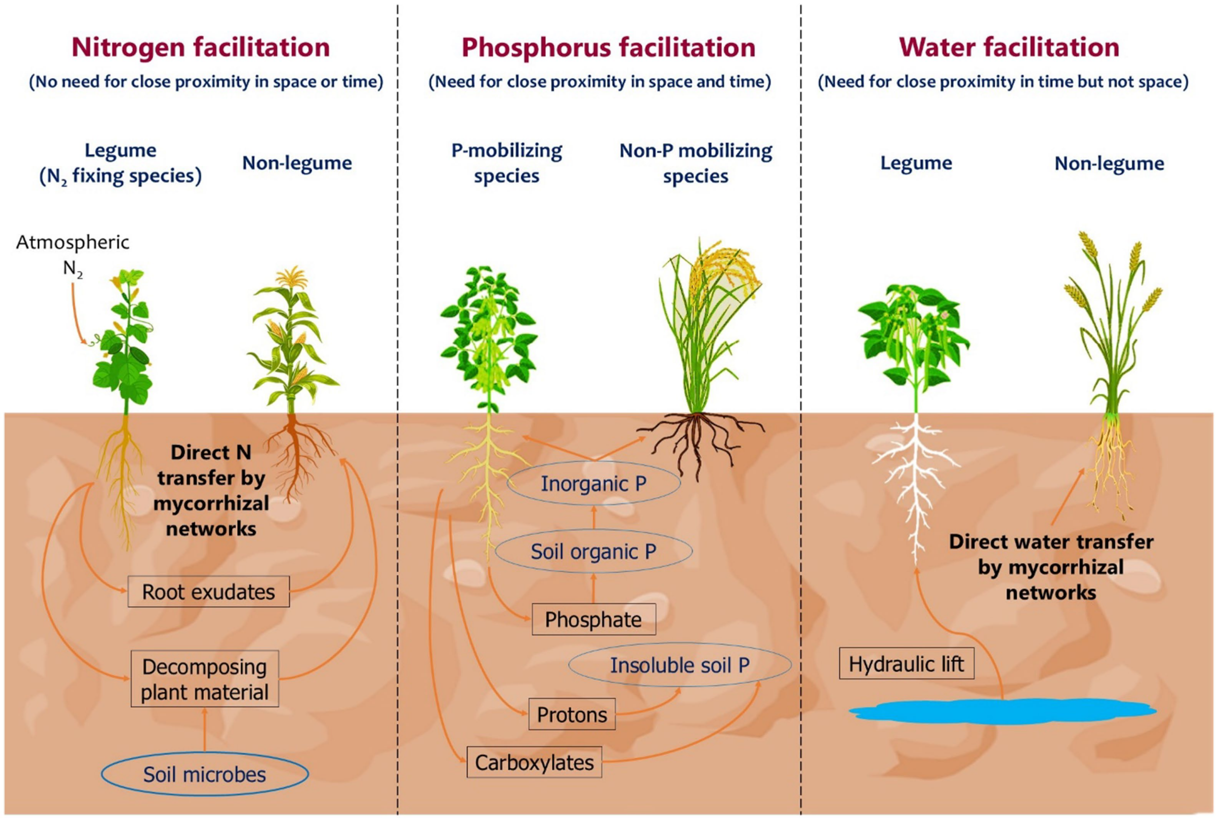

FIGURE 4
The physiological mechanism behind interspecific facilitation in nitrogen, phosphorus, and water acquisition (adapted from Homulle et al., 2021).

sorghum + cowpea intercropping decreased runoff by 20–30% compared to sole sorghum and by 45–55% compared to monocropped cowpea, resulting in a 50% reduction in soil loss. Intercropping systems, particularly with maize and soybean or legumes and cereals, enhance soil structure, increasing aggregate stability by 20% and reducing bulk density by 12% over 3 years (Bhattacharyya et al., 2023). Similarly, Rajanna et al. (2022) reported that intercropping systems increased aggregate stability by 15% and reduced bulk density by 10% over 3 years, enhancing water infiltration and aeration. As anchor crops, legumes effectively enhance soil structure and water infiltration, particularly under semiarid and rainfed conditions, making them ideal for intercropping with fast-growing, shallow-rooted crops. In pigeon pea + maize intercropping, root interactions, and biochemical activities improve soil structure and nutrient storage, especially in P-sorbing soils. This raised organic P storage in micro-aggregates to 84 mg P kg^{-1} in intercrop versus 29 mg P kg^{-1} in sole maize (Chamkhi et al., 2022).

5.2 Chemical properties

In semi-arid areas, legumes such as lablab and soybean increase soil OC, available P, and total N while simultaneously reducing exchangeable cations and C:N ratios compared to weedy fallows (Nigussie et al., 2021). Cuartero et al. (2022) reported that melon + cowpea intercropping increased total soil carbon by 25% and total N by 18% compared to mono-cropping due to higher populations of nutrient-cycling bacteria like rhizobia. Similarly, Cong et al. (2015) found that intercropping maize with wheat or faba bean raised SOC by 4% and organic N by 11%, with carbon and N sequestration rates of 184 kg ha^{-1} yr.$^{-1}$ and 45 kg N ha^{-1} yr.$^{-1}$, respectively. Hussain et al. (2024) found a 20% rise in SOC over 3 years when intercropping soybeans with maize, compared to monoculture maize. Similarly, Virk et al. (2021) observed a 15% increase in SOC over 4 years with clover or vetch in maize + wheat systems, due to increased residue and microbial activity.

Furthermore, legume + cereal intercropping significantly enhances P availability and uptake. A meta-analysis by Tang et al. (2021) on P efficiency in cereal + legume intercrops found a significant increase in P absorption and a soil equivalent ratio for P uptake averaging 1.24. The net effect for P uptake was 3.67 ± 1.00 kg ha^{-1}, with an absolute gain of 6.87 kg ha^{-1} due to intercropping, demonstrating improved P use efficiency and reduced fertilizer need compared to sole crops. In northwest China, intercropping systems like maize + turnip, maize + faba bean, maize + chickpea, and maize + soybean showed higher P acquisition than monocultures, with faba bean's P uptake increasing by 42.4% at flowering. Fertilizer P recovery in intercropping improved from 6 to 30% at 40 kg ha^{-1} and from 5 to 14% at 80 kg ha^{-1} (Yang et al., 2021). Betencourt et al. (2012) found increased P availability in durum wheat + chickpea intercrops due to root-induced alkalization and exudation. Similarly, Guo L. et al. (2023) showed soybean root exudates boost N mineralization by 30% and P availability by 25%. Legumes improve P availability through root exudates like piscidic acid, which releases P from iron-phosphate complexes (Sugihara et al., 2021). Their deep root systems offer drought tolerance and access nutrients from deeper soil layers reducing dependence on synthetic fertilizers and promoting sustainability (Shoaib et al., 2022).

5.3 Biological properties

A study comparing a 30-year maize monoculture with intercropping systems found *Sphingomonas* resistant to monoculture effects, while *Massilia* and *Haliangium* served as sensitive bacterial indicators, highlighting intercropping's role in enhancing soil health and biodiversity (Wolińska et al., 2022). Field experiments with maize + sesame, maize + peanut, maize + soybean, and maize + sweet potato intercropping showed increased microbial diversity, particularly fungi and bacteria, measured by species richness, Shannon index, and evenness. Notably, maize + peanut intercropping yielded the highest bacterial species richness (Xiao et al., 2023).

Legume intercropping significantly enhances soil properties by increasing microbial diversity, which improves nutrient cycling, OM turnover, nitrification, and soil structure. These microbial changes boost plant growth and health, highlighting the benefits of diverse soil bacterial communities in legume intercropping systems. Work done by Song et al. (2007) found that intercropping systems like wheat + faba bean, wheat + maize, and maize + bean increased soil microbial biomass and C: N ratios compared to monocultures. This indicates that intercrops with higher OM foster diverse and active microbial communities, enhancing soil enzymatic activities such as dehydrogenase, urease, and phosphatase. Additionally, Hao et al. (2022) found that maize root exudates increased microbial diversity and biomass by 20%, showing the impact of specific crops on microbial communities. Soil microbial community composition is influenced by environmental factors, fertilization practices, agricultural practices, and planting patterns, which account for around 26.7% of bacterial community variation.

Intercropping impacts microbial community structure, affecting soil P and carbon cycling through changes in microbial biomass phosphorus (MBP) and carbon (MBC). Legume intercropping enhances crop productivity by increasing the presence of N-fixing bacteria like *Bradyrhizobium* and *Skermanella* (Yang et al., 2019). Molecular methods reveal that intercropping enhances rhizosphere bacterial diversity compared to monocropping, increasing the abundance of ammonia-oxidizing bacteria (AOB), ammonia-oxidizing archaea (AOA), and nitrite-oxidizing bacteria (NOB), which are crucial for nitrification. Intercropping with rhizobium inoculation boosts the abundance of total bacteria, archaea, AOB, and AOA, potentially reducing nitrification in the rhizosphere. Therefore, legume intercropping represents an effective strategy to optimize beneficial rhizobacterial colonization, offering a sustainable alternative to chemical fertilizers by naturally enhancing soil health and nutrient cycling.

Legumes play a critical role in altering soil-borne pathogens and reducing pathogenic microbial loads through mechanisms such as biological control and soil health enhancement. Their interactions with beneficial microorganisms, including actinobacteria and rhizobia, significantly contribute to disease suppression and improved crop productivity. For example, *Streptomyces* strains have proven effective in controlling soil-borne pathogens that affect legumes like chickpea and pigeonpea, which are often susceptible to diseases such as wilt and collar rot (Gopalakrishnan and Srinivas, 2019). Similarly, *Sinorhizobium saheli* has demonstrated the ability to suppress root pathogens in arid legumes, enhancing root nodulation and achieving seed yields of up to 1,325 kg ha^{-1} when co-inoculated with other beneficial microbes (Gautam et al., 2015). In addition to pathogen suppression, legumes improve soil fertility through BNF, fostering microbial communities that compete with pathogens for resources (Kalyan et al., 2024). However, the effectiveness of legumes in managing pathogens is influenced by soil conditions and competing microbial communities, which underscores the importance of understanding these dynamics for sustainable agriculture. Despite their benefits, legumes remain vulnerable to specific root diseases, potentially limiting their effectiveness in certain conditions (Pilet-Nayel et al., 2024). Therefore, integrated disease management strategies are essential to balance the benefits and vulnerabilities of leguminous crops, ensuring their success in diverse agricultural systems.

5.4 Soil conservation through legume intercropping

Soil conservation is essential for adapting to climate change, ensuring soil health, and supporting crop growth by providing crucial minerals. However, extreme weather events, such as heavy rainfall and strong winds, can worsen soil erosion. In semiarid regions, practices, like tree planting and establishing hedgerows, help combat wind erosion, while in humid and coastal areas, vegetation cover, contour ploughing, and contour hedgerows are commonly adopted to control soil erosion. Intercropping has proven to be an effective solution to these challenges, especially when combined with conservation practices like cover cropping and mulching, which can reduce erosion by up to 50% (Lal, 2018), thus improving soil integrity and environmental resilience. For example, intercropping cowpeas with maize (two rows of maize with one row of cowpea) reduced runoff by 10% and soil loss by 28% compared to maize monoculture. Similarly, barnyard millet showed the lowest runoff (36% of rainfall), followed by soybean and maize at 37 and 42%, respectively (Tiwari et al., 2023).

In drylands, intercrops like soybean, groundnut, or cowpea with maize, sorghum, or pearl millet have been effective at controlling soil erosion. In mountainous regions like the Himalayas, vegetative barriers have proven to be effective, reducing runoff by 18–21% and soil loss by 23–68% on slopes of 2–8%. Barriers made from pigeon pea, with its dense canopy cover of 95–98%, reduced runoff by 28–29% and soil loss by 2.1 to 2.6 tons per hectare in a sequence with finger millet, kodo millet, and lentil. Converting just 10% of a field to native perennial vegetation can cut sediment runoff by up to 95% and reduce P and N losses by over 85% (Tiwari et al., 2023). Greater plant species diversity enhances soil carbon and N stocks through greater root biomass, improving carbon storage and potentially displacing fossil fuel use. Long-term field experiments conducted since 2003 showed that intercropping systems, such as maize + wheat, maize + rapeseed, and maize + pea, have higher SOC and N compared to monocultures (Wu et al., 2024). These intercropping systems not only yield more grain but also emit 50% less carbon per hectare per millimeter of water than maize monoculture. Furthermore, maize silage intercropped with forage sorghum has demonstrated a 7.3% lower global warming potential compared to maize silage alone.

Intercropping also helps address soil contamination. For example, faba bean intercropped with *Sedum alfredii* and inoculated with a plant growth-promoting endophyte showed improved biomass production and enhanced removal of heavy metals like cadmium (Cd) and lead (Pb) from soils. This improvement is attributed to the synergistic interaction between the legume and the endophyte, which collectively enhanced the plant's ability to tolerate and uptake heavy metals. This intercropping system successfully reduced the concentrations of Cd and Pb in faba beans and maintained its concentration within permissible limits (0–0.2 mg kg^{-1}), making it a viable solution for managing soil contamination (Rezende et al., 2020). Thus, intercropping not only enhances soil health and fertility but also plays a crucial role in climate change mitigation, erosion control, and addressing soil contamination, contributing to sustainable agricultural systems.

6 Yield response to legume intercropping

Legume intercropping has gained recognition for its ability to enhance yields compared to traditional monocultures (Glaze-Corcoran et al., 2020). Intercropping has been consistently shown to improve land-use efficiency (more yield per unit area compared to monocultures), as demonstrated by enhanced Land Equivalent Ratios (LERs). Supporting this, a meta-analysis of 126 studies across 41 countries revealed that intercrops produced 38% more biomass on average, with a mean LER of 1.38, highlighting their superior productivity and resource-use efficiency. Similarly, Feng et al. (2021) observed that maize + peanut and maize + soybean intercropping systems improved land-use efficiency, with LERs increasing by 20–30%, reflecting better resource utilization due to the differing root depths and growth habits of these crops.

Vertical stratification in intercropping systems reduces competition for resources like light and nutrients, enhancing overall productivity. However, the effectiveness of intercropping can vary with soil conditions, and initial root competition may hinder early growth, as seen in pea + barley systems, where pea plants experienced a 15–20% reduction in shoot dry matter (Giuliani et al., 2024). Nevertheless, promising combinations such as N-fixing legumes, deep-rooted species like lucerne, and autumn-sown oilseeds and cereals have shown significant potential. For instance, mean LER values for barley + faba bean intercropping ranged from 1.05 to 1.23 (Salinas-Roco et al., 2024). In sub-Saharan Africa, maize + common bean intercrops achieved LERs of 1.48 to 1.55 (Gidey et al., 2024).

In northwest China, intercropping systems involving faba bean + maize, chickpea + maize, and soybean + maize significantly increased grain yields by 24, 45, and 39%, respectively, illustrating the role of intercropping in boosting productivity while supporting sustainable intensification (Nasar et al., 2024). Biodiversity within intercropping systems also enhances the temporal stability of biomass production (Markos and Yoseph, 2024). Kahraryan et al. (2021) found that optimal intercropping ratios of barley and vetch improved both grain yield and forage quality. In conservation agriculture systems, maize yields ranged from 2,800 to 3,000 kg ha^{-1} under sole cropping conditions. However, when intercropped with legumes, yields significantly improved, reaching 3,609 kg ha^{-1} with groundnut and 3,307–3,576 kg ha^{-1} with common bean (Mupangwa et al., 2021; Dai et al., 2019). Crop complementarity in intercropping systems capitalizes on the unique traits of each species to boost productivity (Pelzer et al., 2020).

Intercropping maize with short-grain cereals or legumes, which have distinct growth periods from maize, results in higher absolute gains compared to monocultures (Kakraliya et al., 2018). In China, high-input intercropping systems with multi-row configurations have achieved yields approximately four times higher than low-input strategies. Both high- and low-input intercropping conserve 16–29% of land and 19–36% of fertilizer compared to monocultures. These gains result from enhanced resource efficiency, nutrient uptake, optimized light interception, and improved water use, along with reduced pest pressure and healthier soils (Yu et al., 2022). Economically, intercropping benefits farmers through reduced input costs, diversified income streams, and access to premium markets. Legume intercropping alone can lower fertilizer costs by 25% and pesticide costs by 30% (Raza et al., 2023). Furthermore, sustainably produced products often command a 10 to 30% price premium, providing economic stability by mitigating risks from fluctuating input prices and market volatility (USDA Economic Research Service, 2023). Table 5 summarizes the distribution and LER figure of the main intercropping systems of selected countries. Through careful crop selection and spatial arrangement, intercropping offers significant environmental and economic benefits, ensuring long-term productivity and resilience.

Optimal spatial arrangements and planting densities are critical for maximizing resource use and yield stability (Gaikwad et al., 2022). For example, planting legumes in wide rows or alternating them with cereals like maize or sorghum enhances sunlight interception and soil nutrient utilization, directly contributing to improved crop productivity (Toker et al., 2024). Feng et al. (2022) demonstrated that spatial configurations like narrow-wide-row relay-intercropping improve light interception and photosynthesis, reinforcing intercropping as an effective strategy for enhancing yields and maintaining ecosystem health. Row intercropping reduces light competition and pest incidence, resulting in healthier crops and higher yields. Similarly, strip intercropping facilitates efficient mechanical operations and optimizes resource distribution, further enhancing yield potential. Mixed intercropping, by creating diverse microhabitats, promotes plant growth and resilience, enabling crops to better withstand environmental stresses and achieve greater productivity (Benmrid et al., 2023). Effective spatial arrangements, such as row and strip intercropping, have been shown to increase yields by 10 to 20% (Liu et al., 2017). Recent studies have also emphasized the potential of soil amendments such as N fertilization and biochar to enhance yield and nutrient efficiency in intercropping systems (Hu et al., 2021; Wang et al., 2023).

6.1 Economics and cost benefit of legume intercropping

Intercropping has consistently demonstrated its ability to improve economic efficiency and deliver greater benefits compared to monocropping across various agricultural systems. This sustainable practice optimizes land and resource utilization, leading to higher

TABLE 5 Distribution and land equivalent ratio (LER) of different intercropping systems in selected countries.

Continent	Country	Intercropping system	LER	References
Africa	Ethiopia	Wheat + Faba bean	1.03–1.17	Maalouf et al. (2022)
	Mozambique	Maize + Cowpea	1.53–1.91	Dimande et al. (2024)
Asia	China	Maize + Soybean	1.33	Nasar et al. (2023)
		Maize + Soybean	1.91-2.13	Chen et al. (2019)
		Maize + Faba bean	0.94–1.47	Xia et al. (2013)
	India	Maize + Soybean	1.1–1.6	Banik and Sharma (2009)
		Rice + Peanut	1.66	Sarkar and Pal (2004)
	Iran	Sunflower + Soybean	0.82–1.28	Hamzei and Seyyedi (2016)
Europe	England	Maize + Faba bean	1.02–1.23	Barker and Dennett (2013)
	Italy	Ryegrass + Clover	1.1–1.2	Giambalvo et al. (2011)
North America	Canada	Pea + Barley	1.13–1.31	Kwabiah (2005)
		Pea + Oat	1.13-1.29	
Oceania	Australia	Wheat + Chickpea	0.97–1.10	Jahansooz et al. (2007)
South America	Brazil	Cowpea + Beet	1.05–1.11	Chaves et al. (2020)

yields and profitability. For instance, maize + soybean strip intercropping has proven highly lucrative, with ideal configurations yielding 23,965 CNY ha^{-1} (Kou et al., 2024). Similarly, in Ethiopia, eucalyptus + maize intercropping outperformed monoculture systems by achieving a land expectation value (LEV) of $3,677.5 USD at a 15% interest rate (Belay and Melka, 2024). Moreover, vegetable intercropping, such as kale with carrots and mustard, enhanced land use efficiency by 184%, surpassing monoculture profitability (Parajara et al., 2024).

Additionally, a meta-analysis by Mudare et al. (2022) highlighted the economic advantages of maize and grain legume intercropping, revealing gross incomes of US$ 3,188 ha^{-1} in China and US$ 1,519 ha^{-1} in Africa, significantly higher than the US$ 1946 ha^{-1} and US$948 ha^{-1} generated by monocropping in these regions, respectively. Among maize-legume systems, maize + soybean intercropping in China delivered the highest gross income of US$ 4,124 ha^{-1}, while in Africa, maize + common bean intercropping with US$ 1932 ha^{-1}. Furthermore, Singh et al. (2021), explored chickpea (*Cicer arietinum* L.) and lentil (*Lens culinaris* Medik.) intercropping with linseed (*Linum usitatissimum* L.) and Indian mustard (*Brassica juncea* L.). Their study found that chickpea and Indian mustard intercropped in a 4:2 ratio yielded the highest net return of Rs. 81,168 ha^{-1}. Similarly, Meena et al. (2024) reported that the chickpea + mustard system (6:2 ratio) in southeastern Rajasthan achieved the best net returns of Rs. 93,681 ha^{-1}, with a benefit–cost (B:C) ratio of 3.11. Despite these advantages, challenges such as management complexity and potential yield reductions must be addressed for optimal decision-making.

7 Potential risks of legume intercropping and possible solutions

Despite their benefits, legume intercropping systems face limitations, often confined to mixed farms or collaborations for biomass supply. Legume intercropping presents several challenges due to its complexity, as it involves growing multiple crops simultaneously in the same field. Challenges, such as nutrient management, difficulties in establishing crops and maintaining optimal legume proportions, increased labor requirements, production costs, etc., hinder widespread adoption (Burgess et al., 2022).

7.1 Complexity in management

Intercropping encounters complexity in various aspects of planting, management, and harvesting, leading to higher labor costs and difficulties in scaling up mechanized farming. Farmers must carefully determine optimal seeding rates, sowing depths, compatible plant combinations, equipment use, herbicide applications, harvesting stage, and marketing options. For example, intercropping large-seeded peas with small-seeded canola involves precise seeding rates, planting depths, and fertilizer placement to effectively capture soil moisture. The multiple passing of seeders results in seedbed compaction and increased labor demands. However, innovations like affordable multi-crop seeders allow single-pass planting of multiple species, while ensuring precision sowing depths, making legume intercropping more feasible (Madsen et al., 2022).

Harvesting intercrops also poses challenges as the crops mature at different times and require multiple harvests. The introduction of a second crop disrupts rotation schedules, adding complexity to farm operations. Harvesting crops with different maturities requires specialized equipment, which may not be accessible to resource-limited farmers. In contrast, strip intercropping, where crops are grown in wider bands, allows for separate harvesting if the strips are wide enough to accommodate existing machinery. However, this method often increases labor demands for managing weeds, fertilizer application, and crop care, increasing production costs and making it less profitable. Grain separation is another significant challenge in intercropping when crops have similar grain sizes, necessitating careful crop combination selection. Farmers have addressed this issue by calibrating combine rotors and fans or developing custom seed separation systems. While effective, these solutions increase labor and equipment costs, highlighting the need for further research to optimize profitability.

To better support legume intercropping, several advancements are necessary. These include developing suitable herbicides for mixed cropping systems, grain separation facilities, and studies on intercropping's impact on crop rotations. Policy measures such as carbon credits and expanded crop insurance options could further encourage adoption. Additionally, farmers need intercropping practices tailored to local conditions, including climate, soil type, and production goals, to optimize productivity (Brandmeier et al., 2021). Overall, while legume intercropping promotes sustainable agriculture and resource efficiency, it requires innovative management strategies, technological advances, and policy support to overcome inherent challenges.

7.2 Complexity in yields

Legume intercropping offers benefits such as weed, pest, and pathogen suppression, but yields vary based on context. Additive intercrops, planted between existing crop rows, can reduce yields due to heightened competition, especially in non-legume systems. In contrast, substitutive intercrops, where a portion of the main crop is replaced to limit competition, can improve per-capita crop yields but may lower overall yield per area. Although legume intercropping generally increases LER and ecosystem benefits, these advantages do not always result in yield gains. Suggesting competition may limit productivity more than pest pressure (Shanmugam et al., 2022).

In semiarid regions, legumes compete with cereals for water, negatively affecting yields. For instance, faba beans reduced soil water availability for intercropped maize, increasing kernel abortion rates and lowering yields (Wang M. et al., 2024). Legumes may also compete for N, inhibiting their N fixation capabilities. High soil N levels reduce legume's ability to fix atmospheric N, impacting growth and yield (Salinas-Roco et al., 2024). In olive agroforestry systems, legume intercropping caused yield reductions of approximately 33% for legumes and 47% for cereals compared to sole cropping, indicating potential negative impacts on associated crops (Amassaghrou et al., 2023). Additionally, grain quality can decline, as seen in pea-canola intercrops, which showed a 6–9% decrease in protein content compared to monocrops (Liu et al., 2024). Despite these challenges, intercropping enhances biodiversity and soil health, indicating a complex relationship between intercropping practices and productivity.

Intercropping systems incur higher costs due to the need for regionally adapted management practices to balance light and water competition effectively. Selecting drought-resistant varieties is crucial for realizing efficient water-use, but may be inaccessible to low-income farmers. Yield benefits are limited in nutrient-rich environments or without drought conditions. Relay intercropping and optimizing strip widths can reduce competition, but these complex systems often deter adoption. Identifying intercrop combinations with complementary architecture and resource needs is essential to enhance productivity and profitability (Seleiman et al., 2021).

7.3 Complexity in other resources

Legume intercropping offers ecological and soil health benefits but faces several challenges that can limit its efficiency and sustainability (Zhu et al., 2023). A major issue is resource competition, as both legumes and companion crops compete for sunlight, water, and nutrients. This competition can be particularly challenging in densely planted, nutrient-deficient systems, often reducing legume productivity. Uneven resource distribution further exacerbates the problem, negatively affecting both legumes and companion crops in intercropped fields (Ananthi and Parasuraman, 2020). Pests and diseases also pose significant challenges. While intercropping can disrupt some pest life cycles, it can also create opportunities for others. Additionally, legumes are vulnerable to various soil-borne pathogens, increasing the risk of disease in mixed cropping systems and complicating pest and disease management (Islam and Ashilenje, 2018). Intercropping requires high labor inputs, including precise planning, staggered planting, and multiple harvests. Mechanization is often difficult due to the diversity of crops used, limiting the efficiency gains typically achieved with machinery (Zhu et al., 2023). Environmental stress factors such as drought, salinity, and soil acidity further hinder legume intercropping by reducing yields and increasing resource competition (Ananthi and Parasuraman, 2020). Despite these challenges, effective management practices and leveraging biological interactions can improve soil health and biodiversity, enhancing the resilience and sustainability of legume intercropping systems.

8 The role of legume intercropping under climate resilience

Intercropping helps create microclimates that reduce soil and canopy temperatures, shielding crops from heat stress. For example, Molla et al. (2023) reported a 2–3°C decrease in canopy temperatures and a 10% yield boost under heat stress in maize + cowpea intercropping. Similarly, Murphy et al. (2021) found pigeon pea intercropping yielded 15% more than monocultures under high temperatures. Diverse rotations in intercropping systems also enhance maize yield and resilience, reducing drought-year losses by 14–89% (Bowles et al., 2020). Intercropping is increasingly recognized as a form of "insurance" against extreme weather and pest pressures due to its ability to enhance system resilience. By combining crops of different growth habits, root systems, and resource requirements, intercropping minimizes the risk of total crop failure during droughts, floods, or temperature extremes (Loreau et al., 2021). When one crop fails due to environmental stressors, disease, or pests, the remaining crops can utilize freed-up resources to offset yield losses (Boincean and Dent, 2019).

Competitive legume intercrops can fill gaps left by failed crops, suppress weeds, and stabilize yields. This resilience has been demonstrated in both irrigated and arid climates, supporting stable agricultural productivity amid climate variability (Ebbisa, 2023). However, the success of intercropping depends on precise management tailored to regional conditions to mitigate competition for light, water, and nutrients (Kremsa, 2021). The success of intercropping under drought conditions often depends on using drought-resistant crop varieties, a challenge for low-income farmers with limited access to such resources. In nutrient-rich or non-drought environments, the yield advantages of intercrops adapted to extreme climates can be minimal, underscoring the importance of selecting appropriate crop combinations based on local conditions (Renwick et al., 2020; Singh et al., 2020). Climate-resilient intercropping systems offer additional benefits, such as reducing reliance on fossil fuel-intensive inputs (Tang et al., 2021) and stabilizing production (Paut et al., 2020) while lowering environmental impacts. However, farmers often face concerns about perceived risks of crop failure and higher implementation costs.

Effective intercropping requires initial experimentation tailored to local conditions, such as climate, farm size, and soil. Technical support and local expertise, based on local data, are crucial (Noy and Jabbour, 2020). To improve adoption, outreach efforts should integrate farmers' perspectives (Snapp et al., 2019). Peer mentoring by early adopters and information networks can help share successes, address challenges, and provide guidance (Bressler et al., 2021). Federal incentive programs could reduce economic risks and support experimentation with intercropping. Cost-share programs help offset initial diversification costs but may involve logistical challenges. Special crop insurance programs could ensure competitive payments during the trial-and-error phase of intercropping adoption (Lithourgidis et al., 2011). While intercropping provides a resilient approach to climate adaptation, its widespread adoption depends on addressing economic and logistical barriers, tailoring strategies to local conditions, and integrating farmer perspectives into outreach and support frameworks. Table 5 depicts the response of legume intercropping across various countries, offering insights into trial methods and climate characteristics.

9 Prospects

To effectively compete with large-scale monocultures, optimizing resource use and crop yield in intercropping systems is essential. This involves a thorough understanding of agronomic practices, including tillage methods, seed rates, crop combinations, plant nutrition, and harvesting techniques, as well as alignment with market demand for simultaneous harvests. Further research on crop genotype and species interactions, focusing on resource availability through niche complementarity, is necessary to refine intercropping practices. This is especially relevant as intercropping enhances agricultural resilience and stability by leveraging context-dependent interactions, pest and disease suppression, system linkages, and microtopographic variations.

Despite extensive research, more studies are needed to explore current trends and integrate findings into practical applications, particularly through on-farm testing. This is especially crucial for intercropping systems involving legumes, which play an important role in sustainable agriculture by efficiently managing N, benefiting non-legume crops in mixed systems. Past research conducted on small plots should be validated through collaboration between researchers and producers to facilitate real-world application and encourage adoption. In evaluating the impact of intercropping on crop rotations, it is essential to assess how these systems affect subsequent productivity, disease management, and soil health. Additionally, integrating diverse climate, soil, crop species, and genotype data into models could better illustrate interspecific interactions under varying conditions, which is vital for assessing productivity, sustainability, and resource efficiency on larger scales. Such approaches provide critical insights needed to optimize intercropping systems and foster resilience in sustainable agriculture.

10 Conclusion

Intensive agriculture, characterized by monocultures, heavy reliance on fertilizers and pesticides, and excessive groundwater withdrawal, results in higher production costs, significant environmental challenges, and long-term threats to sustainability. In contrast, integrating legumes into cropping systems enhances food and livelihood security, reduces environmental impact, and promotes sustainability by improving resource use efficiency, suppressing weed growth, increasing the productivity of non-legume crops, and fixing atmospheric nitrogen, soil carbon sequestration, climate adaptation, and biodiversity enhancement. Although intercropping is more labor-intensive and less mechanized than monocropping, it is particularly well-suited to regions like Asia and Africa, where farms are small, cropping systems are diverse, and a substantial agricultural workforce is available. In these regions, intercropping provides food and nutritional security, helps meet most family needs through family farming, offers insurance against crop failures, and creates employment opportunities. Meanwhile, in developed countries, legume intercropping reduces input requirements such as herbicides, fungicides, insecticides, and fertilizers, improves soil health by sequestering carbon, fixing atmospheric nitrogen, breaking hardpan layers, enhancing porosity, increasing water infiltration, and boosts overall resource use efficiency. Successful adoption of legume intercropping requires collaboration among policymakers, researchers, advisors, and farmers. As the challenges of food security and climate change continue to grow, legume intercropping aligns with the principles of sustainable intensification, blending natural crop synergies with local knowledge and creating resilient, productive agricultural systems.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

KA: Writing – original draft. PP: Resources, Supervision, Writing – review & editing. KP: Writing – original draft, Writing – review & editing, Supervision, Resources, Conceptualization. SV: Writing – original draft, Writing – review & editing, Conceptualization, Methodology, Visualization, Data curation, Supervision, Formal analysis. KT: Data curation, Writing – original draft. MM: Writing – review & editing, Visualization, Methodology, Formal analysis. SR: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration,

Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. AC: Data curation, Formal analysis, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Generative AI was used in the creation of this manuscript.

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