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Mechanism-based Framework of Intercropping for Climate-smart Soil Functions: A Global Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Intercropping—the deliberate co-cultivation of two or more crops in the same space and season—has re-emerged as a cornerstone of climate-smart agriculture because it can raise system resilience while improving soil function. This global review synthesizes evidence on how intercropping, including indigenous and smallholder polycultures, supports climate-smart soil outcomes through (i) biologically mediated nitrogen cycling and (ii) soil organic carbon (SOC) accrual and stabilization. Across regions, intercrops diversify rooting patterns, residue chemistry, and rhizosphere processes, shifting nutrient acquisition from input dependence toward biological regulation. In legume–cereal systems, biological nitrogen fixation, complementary N uptake, and altered microbial enzyme activity can reduce reactive N losses while sustaining yields. In parallel, intercropping can increase SOC by boosting belowground carbon inputs, strengthening aggregation, and promoting microbial processing into persistent forms. Recent studies indicate that intercropping may alter the balance of plant- and microbe-derived carbon contributions and can enhance macroaggregate-associated SOC and microbial necromass—key components linked to

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SOC persistence. However, intercropping outcomes vary by crop identity, spatial configuration, climate, and management intensity, and benefits can be weakened when high external inputs override facilitative interactions. By integrating indigenous knowledge with contemporary soil biogeochemistry, this review proposes a mechanism-based framework that connects intercrop design choices (species traits, temporal niche separation, and spatial arrangement) to measurable soil functions (N retention, greenhouse-gas outcomes, aggregation, and SOC stabilization). The synthesis highlights priority research needs, including standardized indicators for "soil multifunctionality," long-term trials across climate gradients, and co-production approaches that embed farmers' knowledge in scalable climate-smart strategies. Intercropping designs vary widely (strip, row, relay, mixed stands), and reporting of spatial configuration, planting density, residue fate, and management history is sometimes incomplete, reducing comparability and synthesis strength.

Keywords: Intercropping; climate-smart agriculture; nitrogen cycling; biological nitrogen fixation; microbial necromass; mineral-associated organic matter; soil organic carbon stabilization.

1. INTRODUCTION

Agriculture faces the dual challenge of sustainably increasing productivity to meet the food demand of a rapidly growing population and adapting to climate change. Despite significant efforts to develop more adaptive and productive crop cultivars and to improve water and nutrient management practices, the potential of crops to tackle this challenge by optimizing soil resource utilization remains underexplored (Luo et al., 2024). Intercropping is among the oldest soil-stewardship technologies in agriculture, embedded in indigenous and smallholder traditions across Africa, Asia, and the Americas, and increasingly promoted as a modern pathway toward sustainable intensification. Its renewed relevance stems from the convergence of three challenges: the need to sustain yield stability under climate variability, to reduce dependence on synthetic nitrogen inputs, and to rebuild soil organic matter that has been depleted by simplified rotations and intensive tillage. In climate-smart agriculture, practices are valued when they simultaneously contribute to productivity, adaptation, and mitigation (Ngapo et al., 2021; Kapayou et al., 2023). Intercropping is notable because it can influence all three through soil function: it can stabilize yields via risk-spreading and resource complementarity, enhance adaptive capacity by improving soil structure and water relations, and contribute to mitigation by promoting SOC storage and reducing nitrogen-related emissions in favorable contexts (Zhu et al., 2024; Li et al., 2024). Intercropping incorporates the better management of crop and soil environmental factors thereby enhancing the macro and micro climatic standards. The selection of complementary intercrops can occupy different spatial variations leading tocrop intensification along with higher combined productivity as compared the monoculture. The added advantages of intercropping system make it an advanced strategy for climate smart agriculture. The smarter way of plant arrangement in standardized rows with varied spacing allows the better utilization of all available resources to the plant (Sahoo et al., 2024).

A central reason intercropping is a "soil-function practice" rather than only a yield practice is that it reorganizes the belowground environment. By combining species that differ in rooting depth, phenology, rhizodeposition, and residue chemistry, intercrops reshape the rhizosphere's microbial habitat and alter pathways of nitrogen transformation and carbon stabilization. Evidence from long-term field trials shows that intercropping can change soil inorganic N dynamics, microbial biomass N, and the activity of N-acquiring enzymes, while also decreasing certain N losses such as runoff and ammonia volatilization relative to monoculture under comparable fertilization regimes (Wang et al., 2022). This implies that intercropping can shift soil from an "open" N cycle—characterized by surplus reactive N and leakage—to a more regulated cycle where plant demand, microbial immobilization, and biological N inputs are better synchronized (Petrie & Bates, 2017; Ba et al., 2023).

SOC dynamics are similarly sensitive to intercropping. Intercropping can increase carbon inputs (especially roots and rhizodeposits), promote aggregation, and influence microbial physiology in ways that favor the formation of persistent SOC pools. Recent mechanistic work indicates that intercropping may enhance macroaggregate-associated SOC through root-trait-driven microbial necromass accumulation (Zhao et al., 2023) and can regulate plant-versus microbe-derived carbon accumulation by altering soil physicochemical properties and microbial physiological traits (Zhu et al., 2024). These findings matter because persistent SOC is increasingly understood as a product of microbial processing and physical–chemical protection rather than simply the chemical "recalcitrance" of plant residues (Wang et al., 2021).

1.1 Indigenous Knowledge and Global Polyculture Traditions

Indigenous intercropping is not a single "practice" but a family of place-based designs built around food security, labor constraints, cultural values, and long-term soil stewardship. The Mesoamerican milpa (often maize–bean–squash with locally adapted variants) is a widely studied exemplar, increasingly framed as a living laboratory for sustainable intensification because it encodes trait complementarity, diet diversification, and soil protection in one system (Mota-Cruz et al., 2025; Arellano-Wattenbarger et al., 2025). Contemporary scholarship also emphasizes that indigenous and local knowledge systems contain functional hypotheses—about timing, species pairing, and field heterogeneity—that can be tested and refined with modern soil measurements, rather than treated as anecdotal add-ons (Khumalo et al., 2025; Petrie & Bates, 2017; Ba et al., 2023).

Critically, indigenous knowledge is often transmitted as rules of thumb—such as "pair a shallow-rooted cereal with a deeper-rooted legume," "stagger planting to avoid peak competition," or "retain mixed residues as soil cover"—that map closely onto contemporary ecological theory (niche differentiation, facilitation, and complementarity). The challenge for highest-impact research is therefore not whether intercropping "works," but under which contexts it delivers net climate-smart soil benefits, which mechanisms dominate, and how those mechanisms can be translated into scalable designs without erasing the social and cultural foundations that made intercropping viable in the first place.

1.2 Scope and Objective of the Review

This review focuses on intercropping as a driver of climate-smart soil function, emphasizing two coupled pathways: nitrogen cycling (including biological N inputs and N loss mitigation) and SOC accrual with stabilization into persistent pools. The objectives are to synthesize global evidence linking intercrop design to (i) soil N transformations and retention, (ii) greenhouse-gas-relevant outcomes where evidence exists, and (iii) SOC stabilization mechanisms such as aggregation, microbial necromass formation, and physicochemical protection. The review also integrates indigenous knowledge as a scientific resource for hypothesis generation and adaptive design principles, and it identifies research gaps that limit generalization and policy uptake.

2. METHODS FOR LITERATURE SELECTION

For this narrative review, a targeted literature search was conducted across Web of Science Core Collection, Scopus, and Google Scholar, complemented by backward and forward citation tracking from key synthesis papers. The search emphasized peer-reviewed journal articles published primarily from January 2014 through August 2025, while allowing inclusion of earlier foundational mechanistic studies when needed to interpret recent findings. Search strings combined terms for practice, process, and outcome, including variations of "intercropping" or "polyculture" with "nitrogen cycling," "biological nitrogen fixation," "nitrogen transfer," "N2O," "microbial biomass nitrogen," "soil organic carbon," "carbon stabilization," "macroaggregate," "mineral-associated organic matter," "microbial necromass," and "indigenous knowledge" or "traditional ecological knowledge."

Inclusion criteria prioritized field studies, long-term experiments, and quantitative syntheses (meta-analyses and global reviews) that reported soil N indicators (e.g., inorganic N pools, microbial biomass N, enzyme activities, reactive N losses) and/or SOC metrics (total SOC, particulate/aggregate-associated pools, indicators of microbial residues or stability). Studies focused solely on short-term yield without soil measurements were deprioritized. Exclusion criteria included non-peer-reviewed sources where journal provenance was unclear and studies without sufficient methodological description to interpret soil outcomes. Because the review aims at mechanistic interpretation, studies that explicitly measured microbial functional indicators (enzyme activity, microbial biomass, rhizosphere interactions) and SOC stabilization proxies (aggregate fractions, stable SOC pools, microbial necromass) were preferentially used to support the conceptual synthesis (Curtright & Tiemann, 2021; Zhao et al., 2023; Zhu et al., 2024; Li et al., 2024).

3. INTERCROPPING AS A CLIMATE-SMART SOIL STRATEGY: GLOBAL PATTERNS AND CONTEXT DEPENDENCE

Intercropping is practiced across a gradient of objectives and constraints. In many smallholder contexts, it is primarily a risk-management strategy that buffers households against rainfall variability, pest outbreaks, and market shocks by diversifying outputs and spreading labor. In commercial contexts, renewed interest is often linked to input costs, regulatory pressure to reduce nitrogen losses, and emerging carbon-market incentives. The soil-function outcomes of intercropping depend strongly on this context because management intensity can either amplify or suppress biological interactions. A global meta-analysis with experimental validation reported that intercrop overyielding can be weakened under high input regimes, implying that facilitation and complementarity contribute most under moderate or constrained inputs where species interactions matter (Zhu et al., 2023).

This context dependence is not a weakness but an organizing principle. Intercropping benefits are most consistent when the system is designed to create complementary resource use (light, water, nutrients) and when management avoids overwhelming the biological regulation that intercrops can provide. When excessive N is supplied, legumes may down-regulate fixation, cereals may reduce exploratory rooting, and microbial communities may shift toward rapid nitrification and loss pathways, reducing the intercropping “advantage.” Conversely, under moderate N supply and adequate residue return, intercropping can promote microbial immobilization and synchronized N release, while increasing belowground carbon inputs that build SOC.

A recent global synthesis indicates that intercropping can promote soil carbon accumulation on average, but with meaningful variation by system type, climate zone, and intercrop configuration (Li et al., 2024). This finding supports a shift from binary claims (“intercropping increases SOC”) toward mechanism-based prescriptions: which intercrop designs increase carbon inputs, which promote stabilization, and which reduce carbon losses from mineralization under warming and moisture stress.

4. INDIGENOUS KNOWLEDGE AS A MECHANISTIC GUIDE TO INTERCROP DESIGN

Indigenous intercropping systems often embody design principles that align with modern soil science: protect the soil surface, keep living roots for longer periods, and pair species with contrasting nutrient acquisition strategies. The milpa is increasingly described as a model system for integrating ecological intensification with food-system outcomes because it combines functional diversity with cultural continuity. Contemporary analyses frame milpa not only as heritage but as an innovation platform where principles of complementarity can be translated into region-specific designs, including climate-adapted cultivars and altered planting calendars (Mota-Cruz et al., 2025; Arellano-Wattenbarger et al., 2025; Fonteyne et al., 2023).

A key contribution of indigenous knowledge is its attention to temporal dynamics. Many traditional systems stagger planting and harvest dates, which reduces peak competition and increases the period during which living roots supply carbon to soil microbes. This temporal niche separation can influence N cycling by spreading N demand and reducing nitrate accumulation during low uptake periods, potentially lowering loss risk. Indigenous systems also commonly emphasize residue retention and mixed organic inputs, supporting aggregation and SOC formation (Knorr & Augustin, 2025; Melash et al., 2023; Harwood, 2024). Importantly, recent scholarship warns against extracting “techniques” from indigenous systems without engaging the governance, land tenure, and knowledge transmission structures that sustain them. Systematic syntheses on integrating indigenous and scientific knowledge emphasize co-production approaches, where indicators and interventions are jointly designed and evaluated to respect local priorities while enabling generalizable learning (Sabar & Midya, 2024; Imoro et al., 2021).

Scientific evidence also supports that indigenous and locally developed mixed cropping systems can contribute to climate adaptation, though outcomes vary by region and socio-ecological context. A Scientific Reports analysis of indigenous farming methods in relation to climate change underscores both the promise and the need for context-specific evaluation, reinforcing that "what works" depends on local soils, climate, and livelihoods (Khumalo et al., 2025; Sabar & Midya, 2024; Imoro et al., 2021).

5. NITROGEN CYCLING IN INTERCROPPING SYSTEMS

Nitrogen cycling is the most immediately policy-relevant soil pathway for intercropping because reactive nitrogen losses drive water pollution and greenhouse-gas emissions, and fertilizer costs shape farm profitability. Intercropping influences N cycling through multiple, interacting mechanisms: biological nitrogen fixation (BNF) in legumes, altered plant N demand timing, rhizosphere-mediated shifts in microbial N transformations, and changes in soil structure that control oxygen diffusion and denitrification microhabitats.

5.1 Biological Nitrogen Fixation and Complementarity in N Acquisition

In legume–cereal intercrops, BNF can substitute for fertilizer N and can indirectly support the companion cereal by reducing competition for soil mineral N. When legumes rely more on fixation, they tend to take up less soil nitrate, leaving more mineral N available for cereals during critical growth stages. This "N sparing" effect is one of the most robust explanations for intercrop performance under reduced N input conditions. Long-term field evidence also suggests that intercropping can restructure soil N pools and microbial biomass N across crop development stages, indicating that N cycling benefits are dynamic rather than static outcomes measured only at harvest (Wang et al., 2022).

Intercropping can also influence enzymatic pathways related to N acquisition. A meta-analysis found that intercropping increases soil extracellular enzyme activity, supporting the interpretation that plant diversity can enhance microbial processing capacity and nutrient turnover in ways that may improve plant access to organically bound nutrients (Curtright & Tiemann, 2021). While increased enzyme activity can accelerate N mineralization, the climate-smart outcome depends on synchronization: whether released N is captured by plants and microbial biomass or lost via leaching and gaseous pathways.

5.2 Nitrogen Retention, Losses, and the "Trade-off" Framing

A critical advance in recent research is the move from "intercropping increases N use efficiency" as a general statement to "intercropping reorganizes N trade-offs among plant uptake, soil availability, microbial immobilization, and loss." In a long-term experiment, intercropping maize with several partner crops increased maize yield and N use efficiency while decreasing ammonia volatilization and runoff losses relative to monoculture, and it documented changes in microbial biomass N and N-acquiring enzyme activity across growth stages (Wang et al., 2022). This type of evidence supports a mechanistic pathway: intercrops can increase plant N uptake while also reducing the size or duration of the soil mineral N pool that is vulnerable to loss.

The relevance for climate-smart agriculture is that these N trade-offs are sensitive to fertilization regime. When inputs are high, the soil mineral N pool may remain large regardless of plant interactions, and the relative advantage of intercropping can diminish. This aligns with global evidence that high input intensity can weaken intercropping overyielding, implying that facilitation and complementarity are "crowded out" by external resource supply (Zhu et al., 2023).

5.3 Greenhouse-Gas Outcomes: Evidence and Nuance

Nitrous oxide (N_2O) is a key uncertainty because intercropping can both reduce nitrate availability (lowering denitrification substrate) and increase root exudation and microbial activity (which may increase denitrification under wet conditions). A recent meta-analysis across intercropping types found that average effects on N_2O emissions can be nonsignificant overall, but outcomes differ by intercrop category (e.g., cereal–legume vs. other types), fertilizer regime, and soil conditions, emphasizing that climate-smart mitigation claims require contextual qualifiers rather than universal statements (Gui et al., 2024).

This nuance has two implications for research and practice. First, the mechanisms driving N_2O outcomes must be measured alongside emissions—particularly soil mineral N dynamics, moisture/oxygen status, and microbial functional genes or process indicators—so that system designs can be tuned toward mitigation. Second, mitigation assessments must consider the whole

N budget: even if N_2O effects are variable, consistent reductions in nitrate leaching, ammonia volatilization, or fertilizer requirements can still yield net environmental benefits.

5.4 Rhizosphere Mediation and Microbe–Plant Feedbacks

Intercropping changes rhizosphere chemistry and microbial community structure, affecting N transformations and plant nutrient uptake. Recent evidence linking rhizosphere metabolites to microbiome shifts in intercropping provides a mechanistic bridge between plant trait complementarity and nutrient acquisition outcomes (Jiang et al., 2024). These findings strengthen the argument that intercropping should be treated as a “rhizosphere engineering” strategy: the goal is not only to combine species aboveground but to orchestrate belowground interactions that shape nutrient cycling, pathogen suppression, and carbon stabilization.

6. SOIL ORGANIC CARBON ACCRUAL AND STABILIZATION UNDER INTERCROPPING

SOC is central to climate-smart soil function because it integrates multiple benefits: fertility, structure, water retention, and mitigation potential. Yet SOC gains are meaningful for climate outcomes only when carbon is stabilized into pools with long residence times. Intercropping influences both carbon inputs and stabilization processes, and recent work increasingly distinguishes “more carbon entering soil” from “more carbon becoming persistent.”

6.1 Evidence for SOC Accumulation and Drivers of Variability

A global synthesis reported that intercropping can enhance SOC accumulation on average, but with substantial heterogeneity driven by climate, soil type, crop pairing, and management practices (Li et al., 2024). This heterogeneity is expected because SOC formation is constrained by both carbon input and the soil’s protective capacity (aggregation and mineral associations). Systems that increase belowground inputs and promote aggregation are more likely to show SOC increases than systems that only increase aboveground residues that are removed or rapidly mineralized.

Intercropping can also affect SOC by altering microbial processing of plant inputs. A key conceptual development is that microbes are not only decomposers but also producers of persistent SOC through necromass formation, which can be physically protected in aggregates and chemically associated with minerals (Wang et al., 2021). In this view, practices that increase microbial growth efficiency and promote necromass stabilization can increase persistent SOC even if total residue inputs do not dramatically rise.

6.2 Microbial Processing, Carbon use Efficiency, and Necromass Pathways

Microbial carbon use efficiency (CUE) has emerged as a potential lever for SOC formation because higher CUE implies more microbial biomass production per unit carbon consumed, increasing the potential for necromass formation and stabilization. A Nature study synthesizing global evidence highlights microbial CUE as a predictor of soil carbon storage, reinforcing that management practices influencing microbial physiology can alter SOC outcomes (Tao et al., 2023).

Intercropping can plausibly influence CUE by diversifying carbon substrates, sustaining rhizosphere inputs, and moderating nutrient limitations that constrain microbial growth. While direct CUE measurements in intercropping remain limited, mechanistic studies provide supporting evidence that intercropping changes microbial physiological properties and carbon processing pathways. For example, intercropping was shown to increase macroaggregate SOC and microbial necromass carbon relative to sole crops, with root traits implicated as drivers of this necromass-linked stabilization pathway (Zhao et al., 2023).

6.3 Aggregation and Physical Protection of SOC

Soil aggregation is a major stabilization mechanism because aggregates create physical barriers that limit microbial access to organic substrates and generate microenvironments that slow decomposition. Intercropping can promote aggregation by increasing root density, improving soil structure through varied rooting architectures, and enhancing microbial by-products that act as binding agents. Recent work explicitly links intercropping to macroaggregate-associated SOC gains and interprets these gains as outcomes of root-mediated microbial necromass accumulation (Zhao et al., 2023).

Further, a recent Agriculture, Ecosystems & Environment study indicates that intercropping can enhance a stable SOC pool through macroaggregate protection interacting with biochemical recalcitrance, suggesting that stabilization can arise from both physical protection and shifts in organic matter composition (Wang et al., 2025). This finding is important because it moves beyond total SOC change to consider "which carbon" is retained, supporting climate-smart claims that focus on persistence rather than short-term accumulation.

6.4 Plant- Versus Microbe-Derived Carbon Contributions

A persistent debate in SOC science concerns the relative contribution of plant residues versus microbial products to stabilized SOC. Intercropping provides a practical testbed because it alters both plant inputs and microbial communities. Evidence indicates that maize intercropping can regulate plant- and microbe-derived carbon accumulation by influencing soil physicochemical properties and microbial physiology, implying that the pathway to SOC gains may depend on whether the system primarily increases plant-derived inputs, microbial processing into necromass, or both (Zhu et al., 2024).

This distinction matters for design. If SOC gains are primarily microbially mediated, then intercrop designs that sustain rhizosphere activity over longer periods, provide balanced nutrient stoichiometry, and avoid severe microbial nutrient limitation may be most effective. If gains are primarily plant-input driven, then biomass production and residue management dominate. In practice, the two pathways interact: plant traits shape microbial communities, and microbial processing determines whether plant carbon becomes persistent.

6.5 SOC Stability under Climate Change: Mineralization Sensitivity and Stoichiometric Controls

Climate change introduces a second layer of complexity: SOC gains must persist under warming and altered moisture regimes. Recent evidence suggests that intercropping can influence SOC mineralization and its temperature sensitivity, and that these effects may be associated with soil C–N–P stoichiometry and carbon-acquiring microorganisms and enzymes, pointing toward a mechanistic link between nutrient balance and carbon stability (Yang et al., 2025). While broad generalization remains premature, the implication is that intercrops that improve nutrient balance and microbial functional capacity may not only increase SOC but also reduce its vulnerability to accelerated mineralization under warming.

7. INTEGRATING NITROGEN CYCLING AND SOC STABILIZATION: TOWARD A CLIMATE-SMART SOIL FUNCTION FRAMEWORK

A core insight from recent literature is that nitrogen cycling and SOC stabilization are coupled. Nitrogen availability influences microbial growth and residue decomposition; microbial processing influences both N immobilization and the formation of stable carbon. Intercropping can shift this coupled system by creating spatially and temporally heterogeneous rhizospheres, where some zones are N-rich due to fixation and others are carbon-rich due to dense rooting and exudation. These heterogeneities can create conditions for microbial growth that promotes necromass formation (SOC gain) while also increasing microbial immobilization (N retention), potentially aligning productivity with mitigation.

However, coupling can also produce trade-offs. Increased microbial activity can accelerate decomposition and potentially increase CO_2 fluxes, while enhanced root inputs can stimulate priming of existing SOC in some contexts. Whether intercropping yields net SOC gains therefore depends on whether stabilization mechanisms (aggregation, mineral association, necromass retention) keep pace with increased turnover. Evidence that intercropping increases macroaggregate-associated carbon and stabilizes SOC pools suggests that stabilization can dominate under appropriate designs (Zhao et al., 2023; Wang et al., 2025).

Similarly, N outcomes depend on whether the system reduces the vulnerable soil mineral N pool and improves plant uptake synchronization. Long-term results showing reduced N losses and altered microbial N indicators support this possibility (Wang et al., 2022), while meta-analytic evidence indicates that greenhouse-gas outcomes may require tailored designs rather than generic adoption (Gui et al., 2024).

8. TRANSLATIONAL IMPLICATIONS: DESIGNING INTERCROPS FOR MEASURABLE SOIL OUTCOMES

For intercropping to be promoted credibly in high-ranking scientific and policy arenas, recommendations must be framed as design principles linked to measurable soil indicators rather than as universal claims. First, species pairing should be guided by trait complementarity: differences in rooting depth, phenology, and nutrient acquisition strategy should be matched to local constraints such as rainfall seasonality and soil texture. Second, spatial arrangement (row intercropping, strip systems, relay designs) should be chosen to balance facilitation and manageability, especially where mechanization is needed. Third, fertilization strategies must be co-optimized with intercropping. If high N inputs suppress legume fixation and diminish facilitation, then “intercropping plus business-as-usual fertilization” may underdeliver. This is consistent with evidence that high inputs can weaken intercropping advantages (Zhu et al., 2023).

From a soil-carbon perspective, management must favor stabilization pathways. Residue retention, reduced disturbance, and continuous living roots can complement intercropping by promoting aggregation and microbial processing into persistent SOC. Where feasible, monitoring should move beyond total SOC to include indicators of stability such as aggregate-associated SOC and microbial residue proxies, reflecting the mechanistic evidence that intercropping can increase macroaggregate carbon via necromass pathways (Zhao et al., 2023) and can increase stable SOC pools through macroaggregate protection (Wang et al., 2025).

Finally, integrating indigenous knowledge is not only an ethical imperative but also a scientific opportunity. Co-production frameworks emphasize that local knowledge can inform hypothesis generation and practice adaptation, while scientific measurements can clarify mechanisms and boundary conditions, producing designs that are both locally legitimate and broadly informative (Integrating Indigenous and scientific knowledge synthesis; Mota-Cruz et al., 2025; Arellano-Wattenbarger et al., 2025).

9. CONCLUSION

- Intercropping is a practical climate-smart strategy because it improves soil function while supporting stable production, especially under rainfall variability, heat stress, and input constraints.
- The most consistent soil benefits arise when intercrops are designed around functional complementarity—pairing species with contrasting rooting depths, phenology, and nutrient acquisition strategies—so that competition is reduced and facilitation is strengthened.
- Legume-based intercropping can enhance nitrogen self-sufficiency by increasing biologically supplied nitrogen and improving synchrony between nitrogen release and crop uptake, thereby reducing the likelihood of surplus mineral nitrogen in soil.
- Intercropping can strengthen nitrogen retention by promoting microbial immobilization during periods of high nitrogen availability and by increasing plant capture of available nitrogen, which together can reduce leakage pathways such as runoff, volatilization, and leaching.
- Intercropping contributes to soil organic carbon gains primarily through increased belowground carbon inputs (roots and rhizodeposits), longer periods of living-root activity, and more diverse residue chemistry that supports a broader microbial functional repertoire.
- Carbon stabilization is supported when intercropping improves soil aggregation and promotes the formation of protected carbon pools; these effects are most durable when residue return is maintained and soil disturbance is minimized.
- Climate mitigation outcomes are not uniform across all intercrops; they depend on soil moisture regimes, fertilizer intensity, and intercrop configuration, underscoring the need for context-specific design rather than one-size-fits-all recommendations.
- Indigenous and local intercropping knowledge provides validated design logic—such as spatial patterning, temporal staggering, and residue stewardship—that can accelerate effective intercrop innovation when combined with modern soil indicators.

- For policy and scaling, the key shift is to evaluate intercropping using measurable soil-function targets (nitrogen retention, aggregation, stable carbon pools, and resilience indicators) rather than yield alone.
- Overall, intercropping should be advanced as a mechanism-based technology: successful systems deliberately align crop traits, arrangement, and nutrient management to steer soil processes toward higher nitrogen efficiency, stronger carbon stabilization, and improved resilience under climate change.

10. LIMITATIONS

- Evidence is uneven across regions and systems: many studies focus on a limited set of cereal–legume intercrops, while diverse indigenous polycultures and under-represented agroecologies remain less documented with standardized soil measurements. Moreover this is a narrative review which does not follow PRISMA guideline.

- Many experiments are short-term and may not capture slow-changing processes such as persistent soil organic carbon formation, deep-soil carbon dynamics, or long-term shifts in microbial communities that govern stabilization.

- Intercropping designs vary widely (strip, row, relay, mixed stands), and reporting of spatial configuration, planting density, residue fate, and management history is sometimes incomplete, reducing comparability and synthesis strength.

- Soil outcomes are strongly confounded by management intensity. High fertilizer rates, irrigation, pesticide use, or frequent tillage can suppress facilitative interactions, making it difficult to isolate intercropping effects from broader management packages.

- Measurements often emphasize total soil organic carbon or basic mineral nitrogen pools, while fewer studies quantify stabilization-relevant fractions (aggregate-associated carbon, mineral-associated pools, microbial residue indicators) that better reflect climate-smart persistence.

- Greenhouse-gas assessments are inconsistent. Nitrous oxide and methane measurements are not routinely included, and when measured they are often limited in duration or sampling frequency, which can miss emission pulses after rainfall or fertilization.

- Yield and soil-function trade-offs are not always evaluated together; some studies report productivity gains without full nutrient budgets, while others focus on soil indicators without linking them to farm-level feasibility.

- Indigenous knowledge is frequently cited conceptually but is less often integrated through co-designed methods, long-term partnerships, and socio-economic analysis, limiting translation without oversimplification.

- Scaling constraints—labor, mechanization compatibility, seed availability, and market incentives—are not consistently addressed, which restricts conclusions about adoption at landscape or policy scale.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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