Comparative Analysis of Carbon Footprints in Diversified Cropping Systems

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ABSTRACT

Background: The use of diversified cropping systems, which encompass various methods such as crop rotation, intercropping, cover cropping, and agroforestry, has been promoted as an alternative to resource-intensive monocultures in the context of climate resiliency. Agrifood activities have been shown to account for almost one-third of such human-induced emissions, while farm-level crop and livestock production is estimated to produce around half of this total amount. As a result, the investigation of the overall carbon performance of diversified cropping systems has gained the attention of researchers and policymakers alike.

Objective: The purpose of this paper is to review published studies from different sources and present information on the carbon footprint of diversified vs. conventional monoculture cropping methods from 2015 to 2026.

Sources of literature: A systematic search of databases such as Scopus, Web of Science, PubMed, ScienceDirect, and SpringerLink, as well as reports prepared by international organizations such as the FAO and the IPCC yielded 612 papers. Out of that number, only 78 studies manifested certain characteristics and 61 of them represented core primary evidence.

Main discoveries: Literature shows that intercropping of legumes and cereals using rotation-based diversification as well as integration with agro forestry helps reduce carbon footprint of yield and economic output when compared to monoculture since it has low use of synthetic nitrogen, high buildup of soil organic carbon and better land-equivalent ratios. However, impact is very much context sensitive: there are rotation systems that cause bigger carbon emissions per area than monoculture taking into account N2O emissions, and no-till farming combined with diversification does not necessarily win when full life cycle assessment is conducted.

Research gaps: Some of the significant research gaps that still remain are inconsistent definitions of system boundaries among carbon footprint studies, brief trial lengths that are unable to observe SOC equilibria, low visibility of smallholder and tropical rainfed practices, as well as negligible use of remote sensing technology or digital means for monitoring, assessment, and verification (MARV).

Conclusion: It can be inferred that diversified agricultural methods are more likely to help in reducing agricultural carbon footprints, yet they are not necessarily considered the best strategy. However, larger-scale implementation of this approach can only be achieved through collaboration.

Keywords: Carbon footprint, diversified cropping systems, greenhouse gas emissions, crop rotation, intercropping, life cycle assessment, soil organic carbon, climate-smart agriculture

1. Introduction

The issues surrounding agriculture are at the heart of contemporary discussions on climate change. Meanwhile, as China's one of the most important players on the global agrifood market, it is imperative for the country to reduce agri-food emissions. According to the latest estimations provided by the FAO, total emissions from agri-food systems are equal to 16.5 Gt of CO2-equivalent emissions in 2023 since crop and livestock farming itself directly contributes to 8.1 Gt (49%) of agri-food emissions (FAO, 2023). Although livestock is the prime source of emissions on the farm, cropland management methods, such as the use of nitrogen fertilizer, pest management, and tillage, are also vital in the emissions measurements.

In light of this development, crop diversification has become a vital component of climate-smart agriculture. The diversified cropping systems differ from traditional, intensive monoculture systems by introducing various species both in space (intercropping) and time (crop rotation). The hypothesis is that these systems will enable lower production carbon footprints through a number of interrelated mechanisms, Less dependency on synthetic nitrogen fertilizers and reliance on biological nitrogen fixation by legumes; higher soil organic carbon accumulation because of various root types and various residues left; and more effective use of resources through better land equivalency ratios [3, 4].

1.2 Current global scenario

The necessity for decarbonizing cropland management has to a great extent increased in light of fact that although global agricultural GHG emissions have reduced in intensity, they have also grown relatively in absolute terms by 15 percent from 2000 to 2022 according to FAO Stat Yearbook [5, 6]. In addition, since around 2015, there has been much empirical and meta-analytical research done to see whether any particular diversification strategies provide genuine reduction in carbon footprints when full life cycle accounting comes into play or the gains depend on specific soil, climate and management conditions. The research done in China's arid northwest [7], Canada's prairies [8], Pearl River Delta [9] and semi-arid India [10] has produced specific carbon footprints comparisons; however, wider analyses connecting these studies across seas are still rare.

1.3 Need for the review

While numerous case studies exist, there is an inconsistency in the way carbon footprint literature is structured. Despite extensive research in agriculture, soil science, lifecycle assessment, and climate policy. There are different methodologies used to measure emissions, which leads to uncertain results when conclusions need to be derived. Therefore, performing a structured research project needs to be done.

1.4 Objectives of the review

- To compile peer-reviewed literature comparing carbon emissions of diversified cropping systems, such as inter cropping and crop rotation, and conventional crop monocultures.
- To analyze the methods used in calculating carbon footprint, especially whether the assessment process includes soil carbon sequestration.
- To pinpoint areas of agreement and disagreement in this topic, and determine the reasons behind the observed results.
- To figure out ways where more research is needed, as well as ways where new technologies could be used in the study of carbon footprint of diversified cropping systems.

1.5 Scope of the review

This paper concentrates on carbon footprints and related metrics pertaining to greenhouse gas intensity (such as GHGintensity and carbon sustainability index), as recorded in literature for both annual and perennial diversified cropping systems during the time period of 2015 to 2026. Studies only covering livestock systems, forestry not linked to cropland, and studies analyzing purely economic diversification without any explicit carbon or GHG metric are excluded from the review. The review indicates a preference for field trials and meta-analysis studies while making use of the trustworthy data coming from leading agencies such as FAO and IPCC in order to provide global context.

2. Methodology of Literature Review

2.1 Literature search strategy

A structured search was conducted across Scopus, Web of Science, PubMed, ScienceDirect, SpringerLink, and Google Scholar, supplemented by targeted retrieval of institutional reports from the FAO, IPCC, and FAOSTAT emissions databases. The search covered the period January 2015 to March 2026, chosen to capture the period of accelerated methodological development in agricultural life cycle assessment and carbon footprint accounting following the IPCC Fifth Assessment Report.

Search strings combined controlled vocabulary and free-text terms using Boolean operators, for example: ("carbon footprint" OR "greenhouse gas emission*" OR "global warming potential") AND ("cropping system*" OR "crop diversification" OR "intercropping" OR "crop rotation" OR "agroforestry" OR "cover crop*") AND ("life cycle assessment" OR "soil organic carbon" OR "carbon sequestration"). Reference lists of retrieved reviews and highly cited primary studies were hand-searched to identify additional relevant records (snowballing).

Table 1: Literature search strategy

Element	Detail
Databases searched	Scopus, Web of Science, PubMed, ScienceDirect, SpringerLink, Google Scholar; FAOSTAT and IPCC reports
Search period	January 2015 - March 2026
Core search terms	carbon footprint; greenhouse gas emissions; global warming potential; cropping system; crop diversification; intercropping; crop rotation; agroforestry; cover crop; life cycle assessment; soil organic carbon
Boolean structure	(CF/GHG terms) AND (diversification terms) AND (methodology/soil terms)
Supplementary methods	Backward and forward citation snowballing from key reviews and highly cited primary studies

2.2 Inclusion and exclusion criteria

Table 2: Inclusion and exclusion criteria

Criterion type	Criteria applied
Inclusion	Peer-reviewed journal articles and institutional reports; English language; published 2015-2026 (with select landmark studies pre-2015); reports at least one quantitative carbon footprint, GHG emission, or global warming potential metric; field, meta-analytic, or life-cycle-assessment based
Exclusion	Duplicate records across databases; conference abstracts without full text; non-peer-reviewed grey literature (except designated FAO/IPCC reports); studies lacking a quantifiable carbon/GHG metric; studies focused solely on livestock systems unconnected to cropland; non-English publications without validated translation

2.3. Study selection process

The selection process followed a PRISMA-style approach adapted for narrative-thematic review. Of 612 records initially identified, 125 duplicates were removed, leaving 487 records for title/abstract screening. Following this screening, 331 records were excluded as not addressing cropping-system carbon footprints directly, leaving 156 full-text articles assessed for eligibility. A further 78 were excluded at full-text stage (predominantly for lacking a quantifiable carbon or GHG metric, or for non-peer-reviewed status), yielding 78 studies meeting the inclusion criteria. Of these, 61 were primary field-based or meta-analytic studies forming the core comparative evidence base, and 17 were review articles or institutional reports used for contextual and background synthesis.

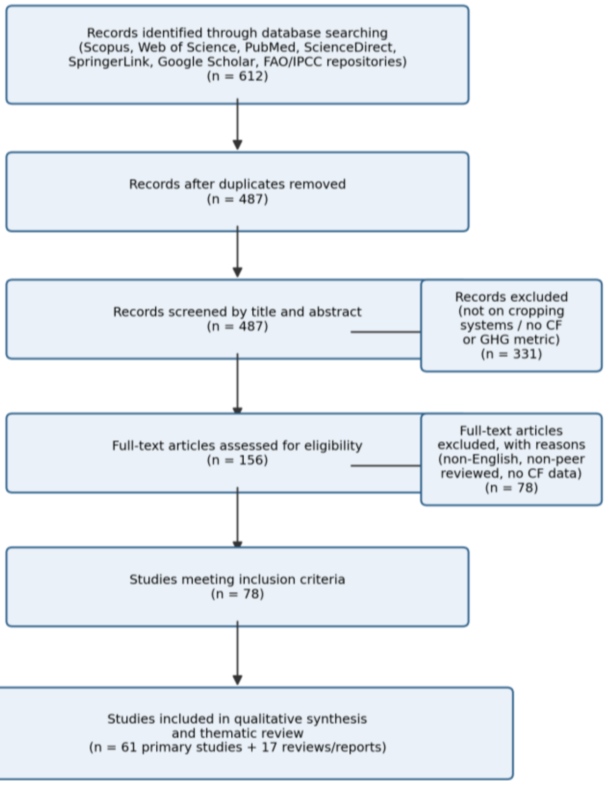

Fig 1: PRISMA-style flow diagram of the literature selection process

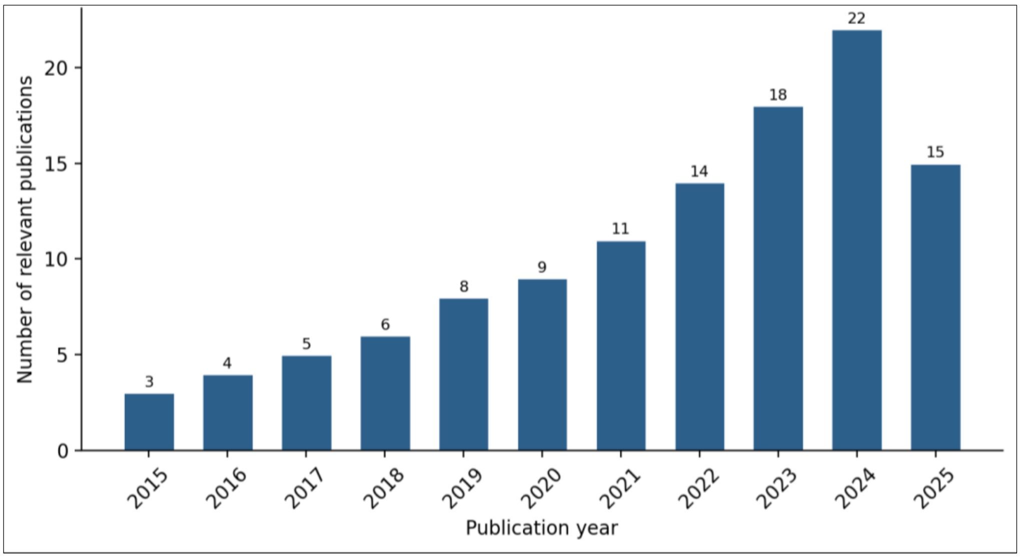

Fig 2: Trend in publications addressing carbon footprints of diversified cropping systems, 2015-2025

As shown in Figure 2, the volume of relevant publications increased markedly after 2019, coinciding with wider adoption of standardized life cycle assessment protocols in agronomy journals and heightened policy attention to agricultural climate mitigation following the IPCC Special Report on Climate Change and Land [11].

3. Literature Review and Thematic Analysis

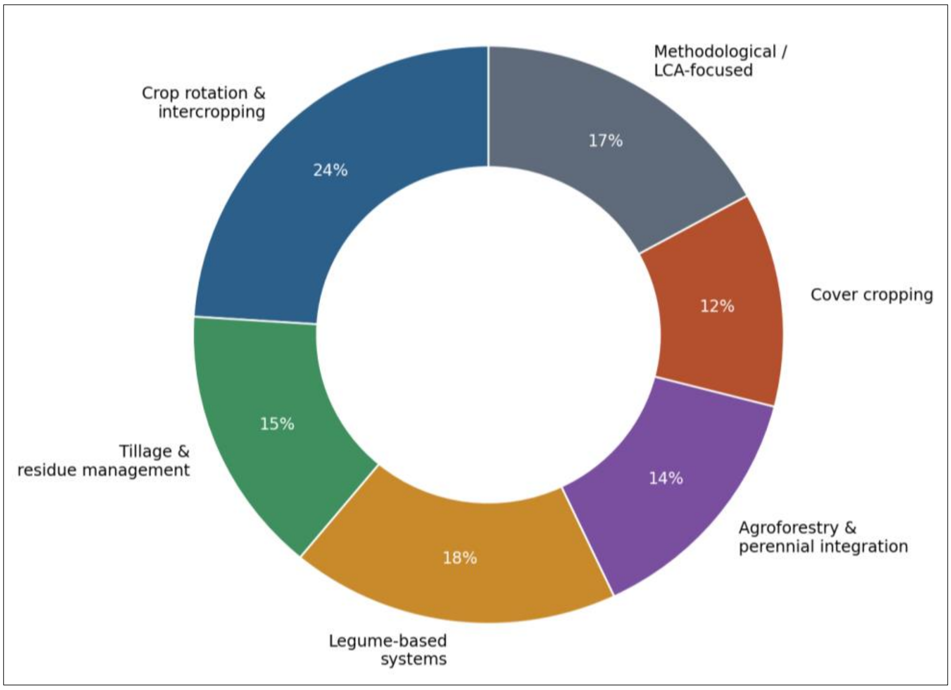

Fig 3: Thematic classification of the 61 primary studies reviewed

3.1 Crop rotation and intercropping

Crop rotation and intercropping constitute the most extensively studied diversification strategies in the carbon footprint literature. In northeastern China, maize-soybean intercropping and rotation systems were found to achieve a lower carbon footprint per unit economic output—45.0 percent lower than continuous maize monoculture—alongside higher profitability, although this benefit came with a partial compromise in grain or energy yield [3]. Similarly, in arid irrigation areas of northwestern China, a three-crop-per-year relay cropping system (wheat-common vetch/maize) achieved carbon footprints 5.3 to 16.4 percent lower than a two-crop wheat-maize intercropping system and 12.2 to 37.6 percent lower than monoculture maize, while simultaneously recording the highest sustainability index among the systems tested [4].

Findings from the Pearl River Delta region of South China reinforce this pattern: maize-rice-forage multicropping systems increased crop productivity by approximately 15 percent relative to a maize-rice-fallow control while reducing carbon footprint per unit area, yield, and economic benefit by 5.1 to 22.8 percent, an effect attributed primarily to significant gains in soil organic carbon under the forage-integrated treatments [9]. Collectively, these studies converge on the conclusion that increasing cropping intensity through diversification, when it enhances soil carbon accrual and resource-use efficiency, can decouple productivity gains from proportional emissions increases.

However, this convergence is not universal. A global meta-analysis of 57 experiments and 225 treatments evaluating tillage, cropping system, and nitrogen management effects on net global warming potential (GWP) and GHG intensity (GHGI) found that crop rotation was associated with 41 to 46 percent greater GWP and GHGI relative to monocropping, even as no-till and reduced nitrogen application substantially lowered these metrics [12, 13]. This apparent contradiction with the China-based intercropping studies illustrates a critical methodological tension in the literature: outcomes depend heavily on whether rotation is compared against an equivalent-intensity monoculture baseline or a lower-intensity one, and whether soil carbon sequestration is fully or only partially accounted for.

3.2 Legume-based diversification and nitrogen dynamics

Legume intercropping and rotation represent a mechanistically distinct pathway to carbon footprint reduction, operating principally through biological nitrogen fixation and consequent reductions in synthetic nitrogen fertilizer demand. A global-scale analysis estimated that grain legumes intercropped with cereals acquire substantial nitrogen from soil and symbiotic fixation, and that shifting a meaningful share of global cereal cropland to cereal-legume intercropping could reduce synthetic nitrogen fertilizer requirements by approximately 26 percent, with corresponding reductions in CO2 and nitrous oxide (N2O) emissions associated with fertilizer manufacture and field application [14, 15].

Field-level evidence supports this mechanism but reveals important nuance regarding N2O dynamics specifically. Wheat-faba bean intercropping in Germany reduced seasonal N2O emissions by 35 percent relative to nitrogen-fertilized wheat monoculture [16], and grass-clover intercropping produced markedly lower annual N2O emissions than nitrogen-fertilized pasture grass [16]. Conversely, at least one perennial grass-forage legume study found that nitrous oxide emissions were highest in treatments containing legumes, even though the overall carbon footprint remained lowest in low-input legume systems because reduced fertilizer-related emissions offset the elevated N2O [17]. This indicates that legume-driven N2O pulses, while real, are typically outweighed by avoided fertilizer-production emissions in full life-cycle accounting, but the net balance is sensitive to legume species, soil nitrogen status, and residue management. A sweet maize-soybean intercropping study in South China similarly found that nitrogen fixation by the legume component improved maize yield and reduced net GHG emissions at moderate fertilizer input levels, while soybean yield itself was somewhat reduced, and soil organic carbon sequestration increased, together lowering the overall carbon footprint and GHG intensity of the intercropped system relative to sole-cropped maize [18]. A more recent wheat/pea intercropping study likewise reported reduced soil nitrate residues and N2O emissions alongside maintained productivity, identifying an optimum nitrogen input level (135 kg N/ha) at which agronomic, economic, and environmental performance were jointly maximized [19].

3.3 Tillage, residue management, and their interaction with diversification

The interaction between tillage regime and cropping diversification is one of the more contested areas of the literature. No-tillage (NT) is frequently promoted alongside diversification as a complementary climate-smart practice, yet meta-analytic evidence on its net effect on greenhouse gas emissions is genuinely mixed. One global meta-analysis of fifty peer-reviewed publications found that NT increased CO2, N2O, and methane (CH4) emissions by 7.1, 12.0, and 20.8 percent respectively relative to conventional tillage, yet still produced a net 7.6 percent reduction in global warming potential once soil carbon sequestration was included [20]. A separate meta-analysis focused on wheat-based rotation systems in China found NT effects on CH4 uptake, N2O emissions, and GWP that were directionally favorable but not statistically robust across all climate zones, with the strongest mitigation benefits confined to temperate zones with alkaline soils and moderate nitrogen application (120 to 240 kg/ha) [21]. The PLOS ONE synthesis of 57 experiments similarly found NT reduced GWP and GHGI by 66 to 71 percent relative to conventional tillage, but noted that results were 2.6 to 7.4-fold different depending on whether full or partial GHG source-and-sink accounting was applied—a methodological sensitivity that recurs throughout this literature [12].

Cover cropping, often deployed as a diversification strategy within otherwise simplified rotations, shows more consistent soil carbon benefits: a global meta-analysis of cover crop effects within corn production systems found that cover crop integration increased soil organic carbon stocks by 7.3 percent on average, with the magnitude of response moderated by soil texture, climate, cover crop species, and tillage regime [22]. In semi-arid irrigated systems, however, a grass-legume cover crop mixture (GBL) exhibited a 58 percent higher carbon footprint than a no-cover-crop control, even though net energy return was 16 to 24 percent greater, illustrating that biomass carbon gains do not automatically translate into a lower footprint once the energy and emissions costs of establishing and terminating the cover crop are included [23].

3.4 Agroforestry and perennial integration

Agroforestry represents the most carbon-intensive form of diversification in terms of sequestration potential, given the incorporation of woody perennial biomass. A systematic review of agroforestry's role in climate mitigation and adaptation reported that tropical homegardens in Kerala, India can sequester up to 2.8 Mg C/ha/year owing to high tree diversity and continuous canopy cover, while silvopastoral systems in Ethiopia and windbreak systems in Senegal sequester approximately 1.5 and 1.7 Mg C/ha/year respectively [24]. Broader estimates across tropical and subtropical case studies suggest well-designed agroforestry systems can sequester 2 to 9 Mg C/ha/year while increasing species richness by up to 40 percent relative to monocropping, with some Gliricidia sepium-based systems in southern India reaching 7.2 Mg C/ha/year [25].

A field-based study of diversified agroforestry integrating arid fruit trees with leguminous, oilseed, and cash crops under limited irrigation in South Asia found that a phalsa-Moringa-potato system achieved the greatest net carbon gain among tested configurations, while also improving farmer profitability and water-use efficiency, indicating that carbon and livelihood benefits can be jointly realized in resource-constrained agroforestry systems [26, 27]. Beyond direct sequestration, agroforestry contributes to footprint reduction indirectly: nitrogen-fixing trees integrated into farming systems have been estimated to supply up to 100 kg N/ha/year, reducing synthetic fertilizer requirements by 30 to 50 percent and thereby lowering associated N2O emissions [24]. Nonetheless, the review literature acknowledges that adoption barriers—including delayed returns from perennial components, land tenure constraints, and limited extension support—continue to restrict agroforestry's contribution to aggregate carbon footprint reduction at scale [24, 28].

3.5 Methodological approaches to carbon footprint quantification

A recurring theme across the reviewed literature is methodological heterogeneity in how carbon footprint is defined and calculated. Most studies apply a life cycle assessment (LCA) approach, quantifying emissions per unit area (CFa), per unit yield (CFy or CFb), and per unit economic output (CFe), while some further compute a carbon sustainability index (CSI) reflecting the ratio of carbon output to input [29]. A carbon budget study of diversified cropping systems in Yunnan Province, southwestern China, employed a cradle-to-farm life-cycle approach across nineteen crop categories and found the region's diversified cropping system functioned as a net carbon sink, with total sequestration of 70.5 Mt CO2-equivalent against total emissions of 37.4 Mt CO2-equivalent, yielding net sequestration of 33.1 Mt CO2-equivalent [30, 31]. The authors explicitly noted that prior studies had generally focused on single crops or a narrow set of cropping patterns, and that biogenic carbon fixed in biomass—such as straw and perennial wood—has not been consistently incorporated into carbon footprint indicators under prevailing ISO 14067 guidance, representing a notable methodological gap that this study sought to address [31].

A four-cropping-system rainfed comparison in India using LCA similarly found that forage- and legume-based rotations reduced carbon footprint and increased carbon efficiency relative to fallow-based systems, while noting that non-renewable energy sources—chiefly diesel and fertilizer—accounted for more than 80 percent of total energy consumed across all systems tested, underscoring that on-farm energy use remains a dominant and somewhat diversification-independent driver of the footprint [10].

4. Comparative Analysis of Previous Studies

Table 3 summarizes the characteristics and principal findings of representative primary studies included in this review, illustrating the diversity of geographic contexts, methodological approaches, and outcome metrics that complicate direct cross-study comparison.

Table 3: Summary of selected primary studies on carbon footprints of diversified cropping systems

Author(s), Year	Location	Methodology	Major findings	Limitations
Zhao *et al*., 2021	Northeastern China	3-yr field trial; LCA-based CF (CFa, CFy, CFe)	Maize-soybean intercropping/rotation cut CFe by 45.0% vs. monoculture maize; higher profitability, some yield trade-off	Single agro-climatic zone; short duration
Liu *et al*., 2022	Northwestern China (arid)	3-yr field experiment; 5 cropping systems compared	Three-crop relay system had lowest CF and highest sustainability index (0.94)	Irrigation-dependent context; limited to arid zone
Lin & Liu, 2025	Canadian Prairies	Multi-ecoregion field-based CF assessment	Diversified/soil-health systems net CO2e withdrawal; market-driven system net emitter	Long-term SOC dynamics still uncertain
Rajpoot *et al*., 2024	Rainfed India	LCA across 4 cropping systems, 2018-2022	Forage/legume rotation lowered CF and raised carbon efficiency; energy inputs dominated by diesel/fertilizer	Energy data self-reported; limited replication
Zhang *et al*., 2024	Yunnan, SW China	Cradle-to-farm LCA across 19 crops, regional scale	Diversified system was a net carbon sink (33.1 Mt CO2eq net sequestration)	Regional aggregation masks farm-level variability
Chen *et al*., 2023	Pearl River Delta, China	2021-2023 field trial; 3 multicropping systems	Maize-rice-forage system cut CF by 5.1-22.8%; raised productivity ~15%	Two-year duration; single soil type
Sun *et al*. (PLOS ONE), 2016	Global (meta-analysis)	57 experiments, 225 treatments, meta-analysis	NT and perennial cropping lowered GWP/GHGI; rotation raised GWP/GHGI by 41-46% vs. monocropping	Full vs. partial accounting yields divergent results
Kumar *et al*., 2025	Global (review)	Systematic review, cereal-legume systems	Cereal-legume intercropping could cut N fertilizer use ~26%, lowering CF	Evidence base skewed toward temperate cereals
Senbayram *et al*., 2015	Germany	Field N2O flux measurement	Wheat-faba bean intercrop cut seasonal N2O by 35% vs. N-fertilized wheat	Single-season, single-site measurement
Abebaw *et al*., 2025	Sub-Saharan Africa & South Asia	Systematic review, agroforestry systems	Homegardens, silvopasture, windbreaks sequester 1.5-2.8 Mg C/ha/yr	Heterogeneous system definitions across regions
Bijalwan *et al*., 2020	South Asia (semi-arid)	Field experiment; diversified agroforestry	Phalsa-Moringa-potato system had highest net carbon gain and profitability	Preprint; limited peer-reviewed replication at time of study
Poeplau & Don, 2023 (synthesis)	Global (meta-analysis)	Meta-analysis, cover crops in corn systems	Cover cropping raised SOC stocks by 7.3% on average	High variance by soil texture/climate moderators

4.1 Cross-study comparison of carbon footprint outcomes

Several patterns emerge from cross-tabulating the studies in Table 3. First, studies employing full life-cycle accounting that includes soil organic carbon sequestration consistently report more favorable carbon footprint outcomes for diversified systems than studies restricted to direct field emissions alone. Second, the magnitude of carbon footprint reduction associated with diversification varies by more than an order of magnitude across studies (from roughly 5 percent to over 45 percent), reflecting differences in baseline system intensity, climate, and the specific diversification strategy examined. Third, whereas legume-based diversification shows the most mechanistically consistent benefit (via avoided fertilizer emissions), rotation-only diversification without a legume or perennial component shows more equivocal results, occasionally increasing net GWP relative to monocultures under certain accounting conventions [12].

5. Research Gaps and Emerging Trends

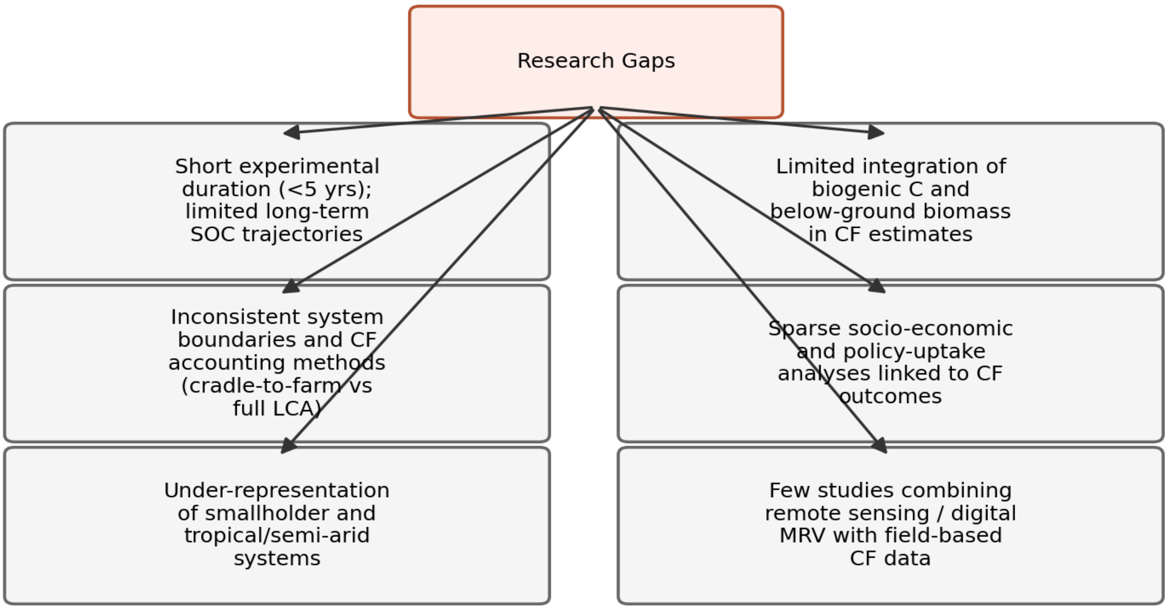

Fig 4: Mapping of key research gaps identified across the reviewed literature

5.1. Unresolved issues and knowledge gaps

- **Inconsistent system boundaries:** studies vary in whether they adopt cradle-to-farm, cradle-to-gate, or partial-accounting boundaries, materially affecting comparability of reported carbon footprint values [12, 31].
- **Short experimental duration:** the majority of field trials span 2-4 years, insufficient to capture the multi-decadal timescales over which soil organic carbon stocks equilibrate under new management [4, 9].
- **Under-representation of smallholder and tropical rainfed systems:** much of the quantitative evidence originates from large-scale, often irrigated systems in China, with comparatively sparse coverage of African and South Asian smallholder contexts beyond selected agroforestry case studies [24, 26].
- **Incomplete treatment of biogenic carbon:** current ISO 14067-aligned practice frequently excludes biomass-fixed carbon (straw, perennial wood) from footprint indicators, likely understating the mitigation contribution of diversified and agroforestry systems [31].
- Limited socio-economic and policy-uptake analysis: few studies connect biophysical carbon footprint findings to farmer adoption incentives, carbon markets, or policy instruments capable of scaling diversification [24, 28].

5.2. Methodological limitations in previous studies

Beyond boundary inconsistency, several recurring methodological weaknesses limit the strength of causal inference in this literature. Many field-based comparisons rely on relatively small sample sizes and single-site trials, limiting statistical power and generalizability. Meta-analyses, while improving statistical robustness, are themselves constrained by the heterogeneity of the underlying primary studies they synthesize, and by publication bias favoring statistically significant or novel findings. Furthermore, most studies report carbon footprint as a static, single-period value rather than as a dynamic trajectory, obscuring transitional emissions that may occur during the establishment phase of a diversified system (e.g., initial soil disturbance for agroforestry establishment) [26].

5.3 Emerging technologies and future developments

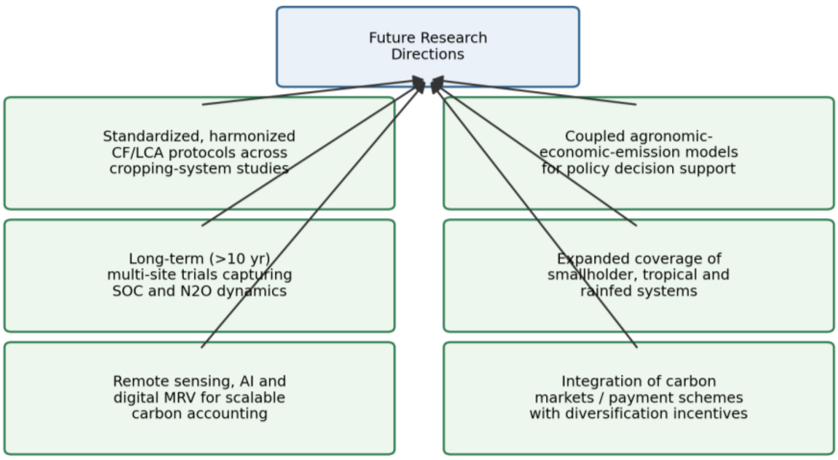

Fig 5: Proposed future research directions emerging from the review

Several emerging developments are likely to shape the next generation of carbon footprint research on diversified cropping systems. Remote sensing and satellite-derived vegetation indices are increasingly used to estimate biomass carbon and monitor cropping intensity at landscape scale, offering a pathway to more cost-effective and spatially extensive carbon accounting than field sampling alone [32]. Digital monitoring, reporting, and verification (MRV) platforms, including AI-enabled decision-support tools, are being piloted to help farmers track soil carbon changes and participate in emerging carbon credit and payment-for-ecosystem-services schemes tied to diversified and regenerative practices [32]. There is also growing interest in coupling agronomic-economic models with process-based GHG emission models to jointly optimize for yield, profitability, and carbon footprint rather than treating these as sequential or independent objectives.

Table 4: Research gaps identified in the reviewed literature

Gap category	Description	Illustrative sources
Methodological boundary	Inconsistent LCA system boundaries (cradle-to-farm vs. partial accounting)	[12, 31]
Temporal	Short trial duration (<5 years) insufficient for SOC equilibration	[4, 9]
Geographic representation	Limited coverage of smallholder, tropical, and rainfed systems	[24, 26]
Carbon accounting scope	Biogenic carbon and below-ground biomass often excluded	[31]
Socio-economic integration	Weak linkage between CF findings and adoption/policy analysis	[24, 28]
Technology integration	Limited use of remote sensing/digital MRV alongside field CF data	[32]

Table 5: Emerging trends in carbon footprint research on diversified cropping systems

Trend	Description	Potential contribution
Remote sensing-based carbon monitoring	Satellite vegetation indices and biomass proxies for landscape-scale carbon estimation	Reduces reliance on costly field sampling; enables scaling
Digital MRV and AI decision support	Farm-level digital tools tracking SOC and GHG proxies in near-real time	Supports carbon market participation and adaptive management
Coupled agronomic-economic-emission modelling	Integrated models optimizing yield, profit, and carbon jointly	Improves policy relevance and farmer-level decision support
Standardized LCA protocols	Harmonization initiatives (e.g., ISO 14067 refinement) for biogenic carbon treatment	Improves cross-study comparability
Carbon markets and payment schemes	Emerging mechanisms linking diversification practices to carbon credits	Provides financial incentive for adoption at scale

6. Discussion

The evidence synthesized in this review supports a qualified but genuine conclusion: diversified cropping systems, on balance, tend to lower the carbon footprint of agricultural production relative to specialized monocultures, but the strength, consistency, and mechanism of this benefit vary substantially by diversification type, geographic context, and—critically—by the accounting methodology applied. Legume-based diversification shows the most mechanistically robust and cross-context consistent benefit, operating principally through avoided synthetic nitrogen fertilizer emissions, a pathway supported by both global meta-analytic estimates [14] and site-specific field measurements across China, Germany, and other temperate contexts [16, 18, 19]. This convergence across independent lines of evidence lends particular credibility to legume intercropping as a near-term, scalable mitigation strategy.

By contrast, the evidence on rotation-only diversification (without a legume or perennial component) and on the tillage-diversification interaction is genuinely mixed rather than merely under-studied. The finding that crop rotation increased GWP and GHGI by 41 to 46 percent relative to monocropping in one large global meta-analysis [12] stands in apparent tension with several China-based field studies reporting substantial carbon footprint reductions under rotation and multicropping [3, 4, 9]. Reconciling this tension requires attention to baseline specification: the meta-analysis compared rotation against monocultures at equivalent management intensity, whereas several of the positive field studies compared diversified systems against comparatively input-intensive or degraded monoculture baselines. This suggests that the carbon benefit of diversification is not an intrinsic property of diversification per se, but is contingent on what specific practice, and what baseline, is being displaced.

Agroforestry integration presents the largest absolute sequestration potential among the reviewed strategies, with reported rates spanning 1.5 to 9 Mg C/ha/year depending on system type and region [24, 25], but its practical contribution to aggregate agricultural carbon footprint reduction remains constrained by adoption barriers rather than by biophysical potential. This points to an important theoretical implication: carbon footprint research has been disproportionately weighted toward biophysical quantification relative to the socio-economic and institutional factors that govern whether documented mitigation potential is actually realized at scale. Future research addressing farmer decision-making, land tenure, and carbon finance mechanisms alongside biophysical measurement would strengthen the policy relevance of this evidence base.

Methodologically, the review underscores that reported carbon footprint values are not directly comparable across studies without careful attention to system boundaries, particularly the treatment of soil organic carbon sequestration and biogenic carbon. Studies applying full life-cycle accounting, including sequestration, systematically report more favorable outcomes for diversified and no-till systems than studies restricted to direct field emissions [12, 31]. This is not merely a technical footnote but a substantive scientific issue: it means that policy conclusions about which practices to incentivize can differ depending on which accounting convention is adopted, underscoring the urgency of methodological standardization efforts such as those aligned with ISO 14067.

Relating these findings to current developments in the field, the increasing availability of remote sensing data and digital

MRV tools offers a plausible pathway to resolving some of the geographic and temporal gaps identified in this review, by enabling lower-cost, longer-duration, and more spatially extensive carbon monitoring than traditional field sampling permits [32]. However, these tools remain in relatively early stages of validation against ground-truth field measurements for cropland soil carbon specifically, and their integration with existing carbon footprint accounting frameworks is not yet standardized.

7. Conclusion

In this review, peer-reviewed information is combined from 2015 to 2026 that gives the picture of the carbon footprint of mixed agricultural cropping systems as compared with the standard monoculture cropping environmental footprint. Various studies demonstrate that intercropping and rotation with legumes systems, as well as agroforestry and cover crops systems lower the carbon footprint, thus decreasing the carbon footprint per ton of crop produced or per USD earned with the help of these systems. Nevertheless, the advantages are not always the same and differ according to approaches used and analysis boundaries considered.

The main importance of this synthesis is to reconcile apparently conflicting findings throughout the literature by identifying accounting method and fundamental characteristics as important moderating variables instead of regarding inconsistent findings simply as inconsistency. The authors propose researchers to implement standardized and full life-cycle accounting standards which provide information about the system boundaries and treatment of soils and biogenic carbon and involve long-run experiments to determine the dynamics of soil carbon stabilization over a longer period than typically accounted for in 2-4 years. For policymakers and practitioners, the research results point at the need to implement legume-based intercropping and rotation as an effective short-term mitigation tool, while emphasizing that agroforestry is the most productive in terms of sequestration per hectare but requires additional policies and financing instruments such as the schemes of carbon payments to overcome constraints to its application caused by delayed payback and land rent issues.

Future investigations should focus on the following: (i) the standardization of carbon footprint measurement rules within the agri-food sector and the life cycle assessment community; (ii) the extension of research evidence toward previously neglected smallholding farming areas, especially in tropical and rain-fed regions; (iii) the use of remote and digital MRV technologies combined with actual measurements in the field to improve the efficiency of carbon measurements over time; and (iv) the establishment of agri-economic emission models to inform policies that take into account productivity, farmers' welfare, and climate change mitigation. Solving these issues would allow solidifying the academic foundation needed for scaling diverse agricultural systems in relation to the global agricultural climate change mitigation agenda.

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