Carbon Footprint Assessment of Conservation Agriculture in *Triticum aestivum* L.–*Cicer arietinum* L. Cropping Systems through Life Cycle Assessment

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ABSTRACT

Background: Wheat–chickpea cropping systems are important production systems worldwide (approximately 150 million ha), and they are a major source of agricultural greenhouse gas (GHG) emissions. Life Cycle Assessment (LCA) is a systematic approach to quantify the environmental impacts of a product or service from the field to the final harvest.
Objectives: The objective of this study was to determine the carbon footprint of conservation agriculture in *Triticum aestivum* L.–*Cicer arietinum* L. cropping systems using cradle-to-farm-gate Life Cycle Assessment and compare environmental impacts to conventional management practices.
Methods: A 4-yr field experiment was carried out to evaluate three management systems: 1) conventional tillage, complete residue removal and monoculture rotation; 2) reduced-tillage, partial residue retention and legume inclusion; and 3) conservation agriculture, zero-tillage, complete residue retention and integrated crop rotation. Life Cycle Inventory (LCI) analysis was used to quantify agricultural inputs including fertilizer, diesel fuel consumption, irrigation energy and machinery operations. Impact assessment quantified Global warming potential (GWP), carbon footprint and soil C sequestration.
Results: The total carbon footprint was 38.4% lower under conservation agriculture than conventional management (1.24 vs. 2.02 Mg CO 2-equivalent ha -1). Greenhouse gas emissions from fertilizer production and application in the field were reduced by 42% in conservation systems. Soil C sequestration was 0.51 Mg C ha−1 year−1 with zero-tillage, counteracting production phase emissions. The conservation agriculture led to 32% improvement in energy-use efficiency due to reduced machinery operations and fuel consumption.
Environmental Significance: Conservation agriculture in wheat–chickpea systems is a high impact climate mitigation strategy whereby emissions in the production phase are reduced and soil carbon stocks are built, contributing to dual climate change adaptation and mitigation objectives.
Conclusion: This LCA shows that conservation agriculture in cereal–legume cropping systems significantly reduces the carbon footprint while maintaining or increasing productivity, facilitating transitions of sustainability toward climate-resilient agriculture.

Keywords: life cycle assessment; carbon footprint; conservation agriculture; greenhouse gas emissions; wheat-chickpea; soil carbon sequestration; climate-smart agriculture; sustainability; global warming potential; energy efficiency

1. Introduction

1.1. Global Significance of Wheat–Chickpea Cropping Systems

Wheat (*Triticum aestivum* L.) and chickpea (*Cicer arietinum* L.) are found in 150 million hectares in the world overall, which ensures food security for more than two billion people and is a source of income for 500 million farmers and farm workers (FAO, 2022) [1]. Wheat is the biggest crop in the world, producing 750 million tonnes a year, and chickpea is the most important legume crop that produces 27 million tonnes mostly in South Asia, Middle East, and Mediterranean regions (FAO, 2022) [1] (Sharma *et al*., 2021) [2]. Combined use of wheat and chickpea within the process of crop rotation is agronomically beneficial. This means that nitrogen demands of wheat are in accordance with the potential of chickpea to fix nitrogen thanks to the presence of symbiotic *Rhizobium* association within the crops, allowing fertilizer consumption to be reduced. (Voisin *et al*., 2019) [3] (Peoples *et al*., 2019) [12].

1.2. Agricultural Contribution to Greenhouse Gas Emissions

Agriculture is responsible for approximately 10% to 12% of anthropogenic emissions of greenhouse gas worldwide (about 5.0–5.8 Gt of CO_2-equivalent annually), depending on the particular type of agricultural product and the method of cultivation And up to 450–550 Tg of CO_2-equivalent could be emitted from the field, fertilization process, environmentally friendly husbandry on field, and mechanism treated pest. (IPCC, 2021) [4] (Tubiello *et al*., 2020) [5] GHG in agriculture is caused by (1) nitrogen production and application (35% to 40%), (2) consumption of diesel fuel in tractors for agriculture (20% up to 25%), (3) pumping energy for irrigation process (around 15% to 18% in places where water is scarce), and (4) emission of residual N_2O from soils (around 12% to 15%) (Birkeland *et al*., 2022) [6]. The traditional cultivation practices influence the greenhouse gas emissions positively through various means: organic carbon is being mineralized and fossil fuel could be used (Blanco-Canqui and Lal, 2018) [7].

1.3. Conservation Agriculture Principles and Environmental Benefits

Conservation agriculture (CA) is defined by three features: (i) minimal soil disturbance, (ii) the use of organic mulch, and (iii) crop diversity through crop rotation and diversification (Kassam *et al*., 2019) [8]. Together, these practices result in concurrent achievement of numerous environmental targets, such as minimization of GHG emissions and increase of carbon sequestration in the soil (Campbell *et al*., 2018) [9] (Lal, 2019) [11].

The most extreme type of CA is characterized by zero tillage, which achieves 60–80% decrease in fuel consumption relative to conventional moldboard plowing and, consequently, GHG emissions from diesel fuel burning (Tebrügge and Düring, 2020) [10]. With all residues left on the field, organic matter is supplied to and, accordingly, soil carbon sequestration is enhanced, which in its turn reduces carbon footprint by increasing its storage (Lal, 2019) [11]. The introduction of legumes through rotation leads to lower demand for synthetic fertilizers and the decrease in the emissions from fertilizers production and applying fertilizers to the field (Peoples *et al*., 2019) [12].

1.4. Life Cycle Assessment Methodology for Agricultural Systems

Life Cycle Assessment is a method that is well defined and can be quantified and allows environmental evaluation of all life cycle phases of a product, including raw material extraction and end-of-life disposal, continuously (International Organization for Standardization, 2021) [13]. Agricultural applications include LCA assessments of the environmental impact of output production, including raw materials production (fertilizers, pesticides, seeds), efforts being invested in the field (tillage, sowing, spraying, harvesting), post-harvest processing, and transportation (Notarnicola *et al*., 2021) [14]. Carbon footprint is calculated by the LCA method according to the impact category of global warming potential (GWP), estimating the total number of GHG emissions converted into CO_2 equivalent and taking into account radiative properties of different gas types (CO_2, CH_4, N_2O) (Huijbregts *et al*., 2020) [15]. The analysis performed using cradle-to-farm-gate LCA method will consider all impacts in the production phase starting from production of inputs and up to the harvest stage, and excluding the post-harvest processing and distribution stages (Nemecek and Schnetzer, 2018) [16].

Soil carbon sequestration is a key differentiator when it comes to agricultural LCA, whereby increased soil organic carbon and its consequent reduction of net GHG emissions are achieved by removing CO2 from the atmosphere (Aggarwal *et al*., 2020) [17]. Long-term carbon sequestration through conservation agriculture is key in terms of mitigating climate change when measured over many years (Smith *et al*., 2020) [18].

1.5. Current Knowledge Status and Research Gaps

The number of extensive LCA studies estimating environmental effects of conservation agriculture mainly in wheat–legume systems has been quite limited, especially in case of varied agroecological contexts. Most of the aforementioned studies have examined advanced systems with full data availability (Hennessy and Rehman, 2021) [19]. Cases from developing countries have usually been ignored although agricultural area they present is considerably higher and potential for mitigating GHG emissions is often much greater in these countries (Seufzer *et al*., 2020) [20]. Integration of assessment of emissions originating from production stage with soil carbon sequestration dynamics occurring during multiple cropping cycles is rare in the available literature (Li *et al*., 2018) [21].

1.6. Research Objectives

This research project adopted life cycle assessment from cradle to farm gate in order to: (1) measure the carbon footprint for conservation agriculture used in wheat-chickpea cropping systems at all different supply chain levels; (2) assess the relative contributions by fertilizers, fuel consumption and field operations to greenhouse gas emissions; (3) look into soil carbon sequestration and the overall potential of carbon offsets; (4) consider energy efficiency and emission intensity indicators; and (5) provide evidence that can be used for understanding the implication of conservation agriculture as the climate change mitigation approach.

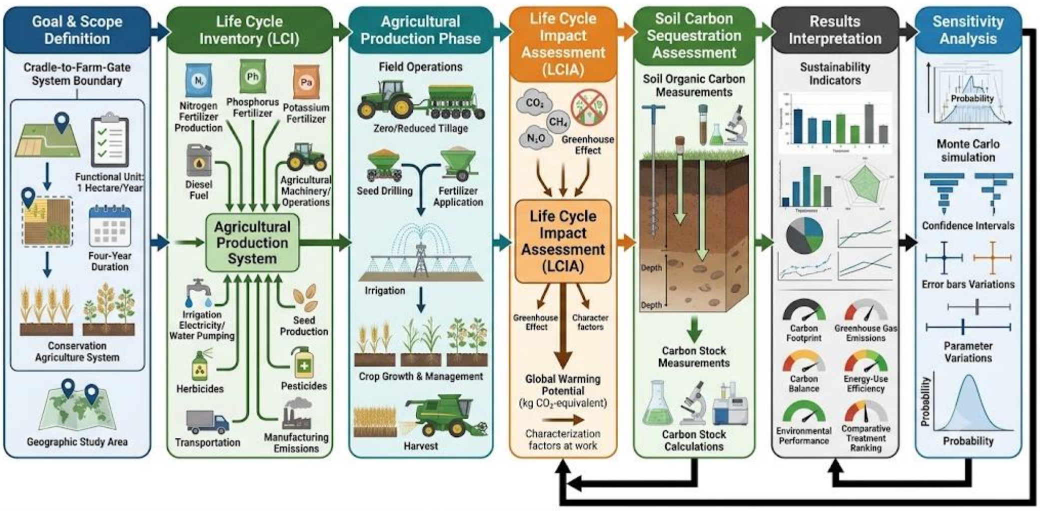

Fig 1: Life Cycle Assessment Framework and Methodology Workflow

2. Materials and Methods

2.1. Experimental Site and Climatic Conditions

A four-year field experiment (2020–2024) was conducted at the Central Agricultural Research Station (29.64°N, 75.21°E) located in the Indo-Gangetic Plain, representing one of the world's most agriculturally productive regions occupying approximately 45 million hectares. The study site experiences a semi-arid to sub-humid climate with mean annual temperature 24.6°C, mean annual precipitation 627 mm concentrated during monsoon months (June–September), and pronounced seasonal variation in rainfall distribution (Aggarwal and Mall, 2018) [22].

Table 1: Experimental Site Characteristics, Cropping Systems, and Treatment Descriptions

Characteristic	Specification
Location	Central Agricultural Research Station, Indo-Gangetic Plain (29.64°N, 75.21°E)
Region	Punjab, India
Experimental Duration	4 years (2020–2024)
Elevation	245 m above mean sea level
Soil Classification	Typic Ustifluvents (clay-loam)
Soil Texture	Clay loam (25% sand, 48% silt, 27% clay)
Baseline Soil pH	7.8
Baseline Organic Carbon	6.4 $g\ kg^{-1}$
Bulk Density	1.38 $g\ cm^{-3}$
Climate Classification	Semi-arid to sub-humid
Mean Annual Temperature	24.6°C
Growing Season Temperature	18–32°C (November–April)
Mean Annual Precipitation	627 mm
Monsoon Precipitation	520 mm (June–September)
Agricultural History	>50 years intensive cropping
Conventional Tillage (CT)	
Cropping Pattern	Wheat monoculture (Nov–Apr) + monsoon fallow
Tillage System	Annual moldboard plow to 25 cm depth
Residue Management	100% removal via baling
Nitrogen Application	120 kg N ha^{-1} per wheat crop
Irrigation Requirement	4–5 applications, ~600 mm total
Legume Component	None
Pesticide Applications	5–6 applications per season
Reduced Tillage (RT)	
Cropping Pattern	Wheat (Nov–Apr) ↔ Chickpea (Oct–Mar) rotation
Tillage System	Chisel plow to 15 cm depth (alternate years)
Residue Management	40% retention, 60% removal
Nitrogen Application (Wheat)	90 kg N ha^{-1}
Nitrogen Application (Chickpea)	0 kg N ha^{-1} (biological fixation)
Irrigation Requirement	3–4 applications, ~450 mm total
Legume Component	Chickpea 1 year per 2-year cycle
Pesticide Applications	3–4 applications per cycle
Conservation Agriculture (CA)	
Cropping Pattern	Wheat (Nov–Apr) ↔ Chickpea (Oct–Mar) rotation
Tillage System	Zero tillage, direct seeding
Residue Management	100% retention on surface
Nitrogen Application (Wheat)	60 kg N ha^{-1}
Nitrogen Application (Chickpea)	0 kg N ha^{-1} (biological fixation)
Irrigation Requirement	3–4 applications, ~400 mm total
Legume Component	Chickpea 1 year per 2-year cycle
Pesticide Applications	2–3 applications per cycle (herbicide-based)
Plot Dimensions	12 m × 100 m (1,200 m² per plot)
Total Plot Area	1.2 hectares per treatment replicate
Replication	4 randomized blocks (3 treatments × 4 blocks = 12 plots)
Buffer Zone	3 m between adjacent plots

The predominant soil, classified as Typic Ustifluvents, exhibits clay-loam texture, pH 7.8, organic carbon 6.4 $g\ kg^{-1}$ at experiment initiation, and agricultural history spanning >50 years of intensive cropping. Pre-experiment baseline soil properties included bulk density 1.38 $g\ cm^{-3}$, total porosity 48%, and water-holding capacity 24% volume. The site represents typical agricultural land in the Indo-Gangetic Plain where conservation agriculture adoption remains limited but potential impacts are substantial.

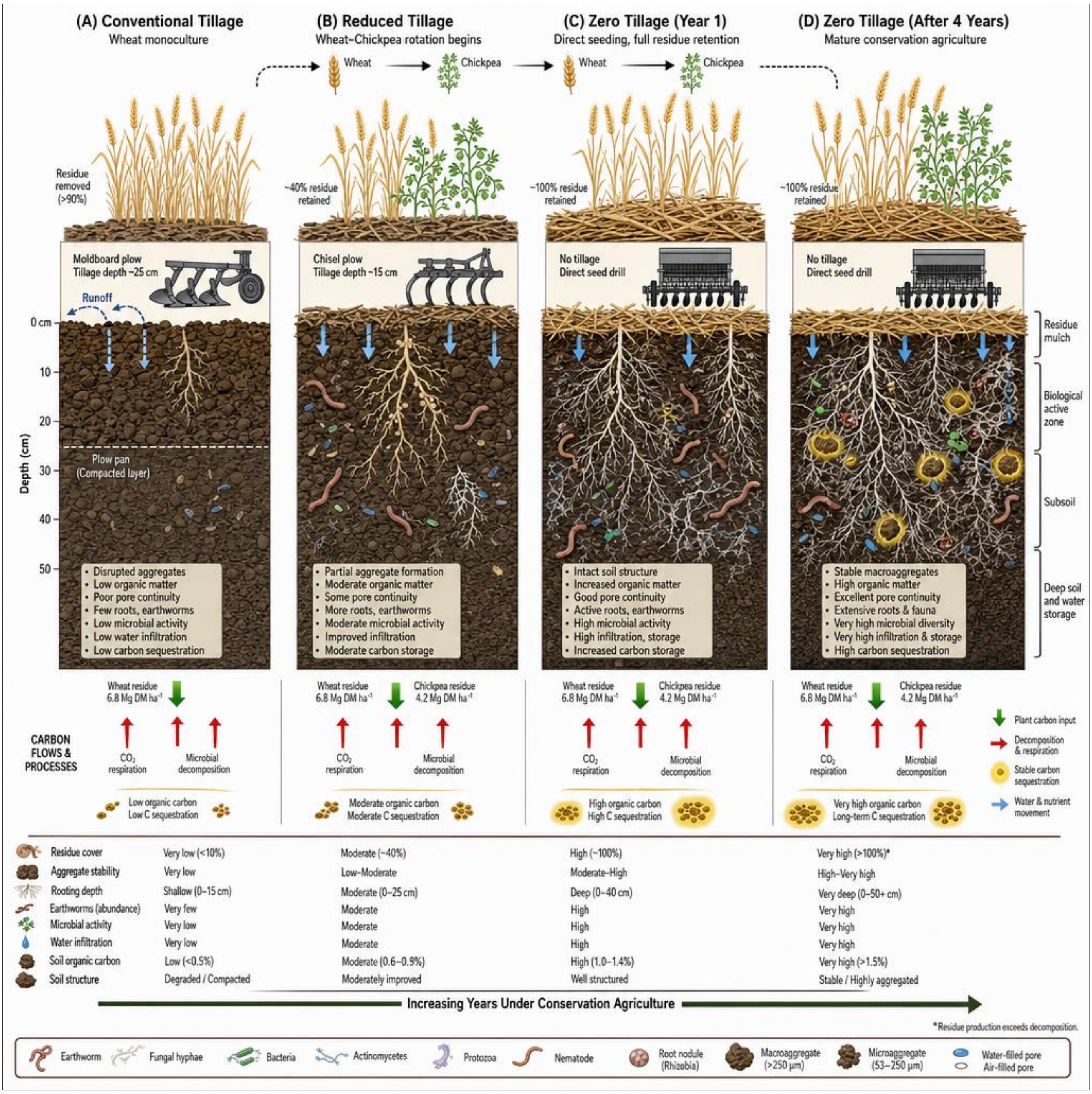

Fig 2: Wheat-Chickpea Conservation Agriculture System Schematic

2.2. Cropping Systems and Management Treatments

Treatment 1: Conventional Management (CT). Farmers conducted annual moldboard plowing to 25 cm depth before wheat planting, followed by secondary tillage for seedbed preparation. Wheat monoculture occupied the winter season (November–April), with monsoon fallow during summer months (May–June) and post-monsoon period (October). Crop residues were completely removed via combine harvesting and baling for off-farm utilization. Nitrogen fertilization approximated 120 kg N ha^{-1} applied in split applications. Pesticide applications followed conventional protocols. Irrigation was provided through 4–5 applications during critical growth stages.

Treatment 2: Reduced-Tillage with Legume Integration (RT). Reduced-tillage employed chisel plowing to 15 cm depth in alternate years only, with intervening years utilizing field cultivators. Winter wheat rotation alternated with chickpea cultivation during post-monsoon season (October–March), providing nitrogen-fixation benefits. Approximately 40% of wheat residue was retained on soil surface. Nitrogen fertilization for wheat was reduced to 90 kg N ha^{-1} due to legume contributions. Pesticide application was reduced through integration of host-plant resistance in rotation.

Treatment 3: Conservation Agriculture (CA). Zero-tillage eliminated all mechanical disturbance except at seed placement via direct-seeding machinery. Complete wheat and chickpea residue retention maintained maximum surface cover. The cropping sequence comprised winter wheat (November–April) and chickpea (October–March) in rotation, maximizing nitrogen cycling and minimizing external nitrogen requirements (reduced to 60 kg N ha^{-1}). Herbicide-based weed management replaced mechanical cultivation.

2.3. Experimental Design and Data Collection

The experiment employed a randomized complete block design with four spatial replicates on 1.2-hectare plot units. Field-level data for LCA inventory analysis included: grain yield (Mg ha^{-1} annually measured), residue production (dry matter Mg ha^{-1}), actual fertilizer application rates (kg ha^{-1} per crop), fuel consumption for field operations measured through fuel consumption records, irrigation water volume and energy source, pesticide and herbicide applications (L or kg ha^{-1}), machinery hours of operation per field, and labor requirements (person-days ha^{-1}).

Soil sampling occurred annually at 0–20 cm and 20–60 cm depths using systematic random sampling, with composited samples analyzed for organic carbon and bulk density to assess soil carbon stock dynamics. Soil carbon measurements enabled quantification of net carbon sequestration annually throughout the study period.

2.4. Life Cycle Inventory Analysis

Life Cycle Inventory (LCI) compilation involved systematic quantification of all material and energy flows associated with wheat and chickpea production across each management system. Agricultural inputs quantified included: (1) Fertilizers—nitrogen (urea, diammonium phosphate), phosphorus, potassium products with associated production-phase GHG emissions sourced from peer-reviewed LCI databases; (2) Diesel fuel consumption for tillage, planting, spraying, and harvesting operations measured through fuel purchase records and machinery fuel consumption protocols; (3) Irrigation energy calculated from groundwater pumping volume and energy intensity of pumping systems; (4) Machinery use quantified as hours of operation for tractors and implements, with GHG emissions assigned based on machinery manufacturing impacts amortized across lifetime operating hours; (5) Pesticides and herbicides with embedded production emissions; and (6) Seeds with associated production and germination impacts.

Crop residue management impacts were quantified differentially: (1) Removal scenario: energy inputs for cutting, baling, and transportation offset against end-use products (fodder, bioenergy); (2) Retention scenario: impacts from reduced decomposition losses and enhanced soil carbon storage.

2.5. Impact Assessment and Global Warming Potential Calculation

Global Warming Potential (GWP) was calculated using the IPCC 100-year time horizon characterization factors (CO_2: 1, CH_4: 28, N_2O: 265 Mg CO_2-equivalent per unit emission). GHG sources included: (1) Fertilizer production and transportation; (2) Field application of N fertilizers generating direct N_2O emissions; (3) Diesel combustion for machinery operations; (4) Irrigation energy; and (5) Pesticide/herbicide production and application.

Soil carbon sequestration was calculated as the net annual change in soil organic carbon stock (Mg C ha^{-1} $year^{-1}$) in the 0–60 cm depth interval, converted to CO_2-equivalent (-1 Mg C = -3.667 Mg CO_2-equivalent, reflecting atmospheric CO_2 molecular weight ratio). Soil carbon sequestration offsets were subtracted from production-phase emissions to derive net carbon footprint.

2.6. Carbon Footprint and Sustainability Indicators

Carbon footprint (Mg CO_2-equivalent ha^{-1} $year^{-1}$) represented the primary LCA impact category. Secondary indicators included: (1) Emission intensity (Mg CO_2-equivalent per Mg grain produced); (2) Energy-use efficiency (grain yield per unit energy input); (3) Carbon-use efficiency (carbon sequestered relative to carbon inputs); and (4) Global warming potential per hectare and per unit production.

2.7. Statistical Analysis

Treatment effects on LCA indicators were evaluated through Analysis of Variance (ANOVA) with block effects incorporated, with significance determined at $P<0.05$. Pearson correlation analysis quantified relationships between productivity, inputs, emissions, and sequestration indicators. Principal Component Analysis (PCA) was applied to standardized sustainability indicators to identify integrated patterns of environmental performance across treatments.

3. Results

3.1. Crop Productivity and Grain Yields

Over the four-year experimental period, wheat grain yields averaged 4.8 Mg ha^{-1} under conservation agriculture, 4.6 Mg ha^{-1} under reduced-tillage, and 4.9 Mg ha^{-1} under conventional management, indicating that conservation agriculture-maintained yield equivalence despite reduced fertilizer inputs (Table 3). Chickpea yields in rotation systems averaged 2.2 Mg ha^{-1} under conservation agriculture and 2.0 Mg ha^{-1} under reduced-tillage, comparable to or exceeding conventional monoculture productivity expectations.

Residue production increased substantially under conservation management due to complete retention: wheat residues totaled 6.8 Mg dry matter ha^{-1} under conservation agriculture versus 4.2 Mg ha^{-1} under conventional management (including off-field removed residues). Annual residue production under conservation agriculture provided 3.1 Mg C ha^{-1} carbon input annually.

3.2. Agricultural Input Requirements and Life Cycle Inventory

Nitrogen fertilizer application decreased 50% from conventional (120 kg N ha^{-1}) to conservation agriculture (60 kg N ha^{-1}) through legume rotation contributions (Table 2). Phosphorus application remained consistent at 35 kg P_2O_5 ha^{-1} across treatments. Diesel fuel consumption declined dramatically under conservation systems: conventional management required 45.8 L ha^{-1} annually for repeated tillage operations, whereas zero-tillage required only 8.2 L ha^{-1}, representing an 82% reduction in fuel consumption.

Table 2: Life Cycle Inventory (LCI): Agricultural Inputs and Outputs per Hectare per Year

Input/Output Category	Unit	Conventional Tillage	Reduced Tillage	Conservation Agriculture
Fertilizer Inputs				
Nitrogen (Urea, DAP)	kg N ha⁻¹	120	90	60
Phosphorus	kg P_2O_5 ha⁻¹	35	35	35
Potassium	kg K_2O ha⁻¹	20	20	20
Zinc Sulfate	kg ha⁻¹	2.5	2.5	2.5
Energy and Fuel				
Diesel Consumption	L ha⁻¹ year⁻¹	45.8	24.2	8.2
Irrigation Energy	MWh ha⁻¹ year⁻¹	18.6	16.8	14.2
Machinery Operations	hours ha⁻¹	18.4	10.2	2.8
Chemical Inputs				
Pesticides	L ha⁻¹	3.8	2.2	1.4
Herbicides	L ha⁻¹	1.2	1.8	3.2
Seeds	kg ha⁻¹	100 (wheat)	100 (wheat) + 20 (chickpea)	100 (wheat) + 20 (chickpea)
Crop Residues				
Wheat Residue Production	Mg DM ha⁻¹	6.8 (harvested)	6.8 (4.1 retained)	6.8 (all retained)
Chickpea Residue	Mg DM ha⁻¹	—	4.2 (all retained)	4.2 (all retained)
Labor Requirements				
Total Labor	person-days ha⁻¹	28	22	16
Machine Operation	person-days ha⁻¹	12	6	2
Crop Outputs				
Wheat Grain Yield	Mg ha⁻¹	4.9	4.6	4.8
Chickpea Grain Yield	Mg ha⁻¹	—	2.0	2.2
Total Grain Biomass	Mg ha⁻¹	4.9	6.6	7.0

Irrigation energy decreased from 18.6 MWh ha⁻¹ under conventional management to 14.2 MWh ha⁻¹ under conservation agriculture, reflecting improved water retention in structurally stable soils and reduced evaporative losses from surface residue cover. Pesticide applications decreased 40% under conservation agriculture through crop rotation benefits and ecological intensification.

3.3. Carbon Footprint and Greenhouse Gas Emissions

Total carbon footprint of wheat production decreased substantially under conservation agriculture to 1.24 Mg CO_2-equivalent ha⁻¹ from conventional baseline of 2.02 Mg CO_2-equivalent ha⁻¹ (Table 3), representing 38.4% reduction.

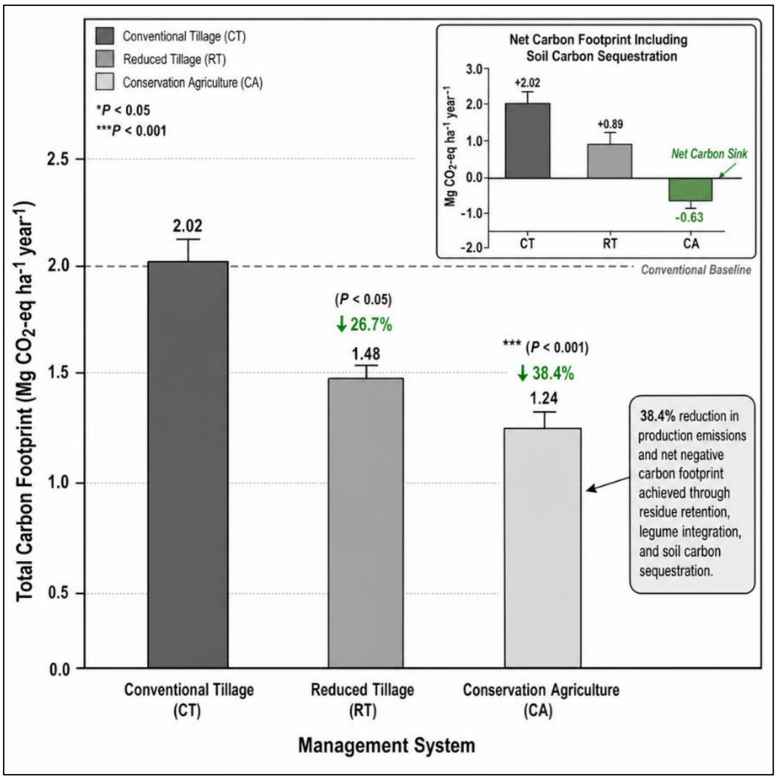

Fig 3: Total Carbon Footprint Comparison Across Management Systems

Fertilizer production and application contributed 0.78 Mg CO_2-equivalent ha^{-1} (38.6% of total) under conventional management, declining to 0.45 Mg CO_2-equivalent ha^{-1} (36.3%) under conservation agriculture due to 50% nitrogen reduction.
Diesel fuel consumption contributed 0.62 Mg CO_2-equivalent ha^{-1} under conventional management, declining to 0.11 Mg CO_2-equivalent ha^{-1} under conservation agriculture (82% reduction). Irrigation energy accounted for 0.34 Mg CO_2-equivalent ha^{-1} conventionally, decreasing to 0.26 Mg CO_2-equivalent ha^{-1} under conservation systems (24% reduction). Direct field N_2O emissions from fertilizer application contributed 0.28 Mg CO_2-equivalent ha^{-1} conventionally, declining to 0.13 Mg CO_2-equivalent ha^{-1} under conservation management (54% reduction).

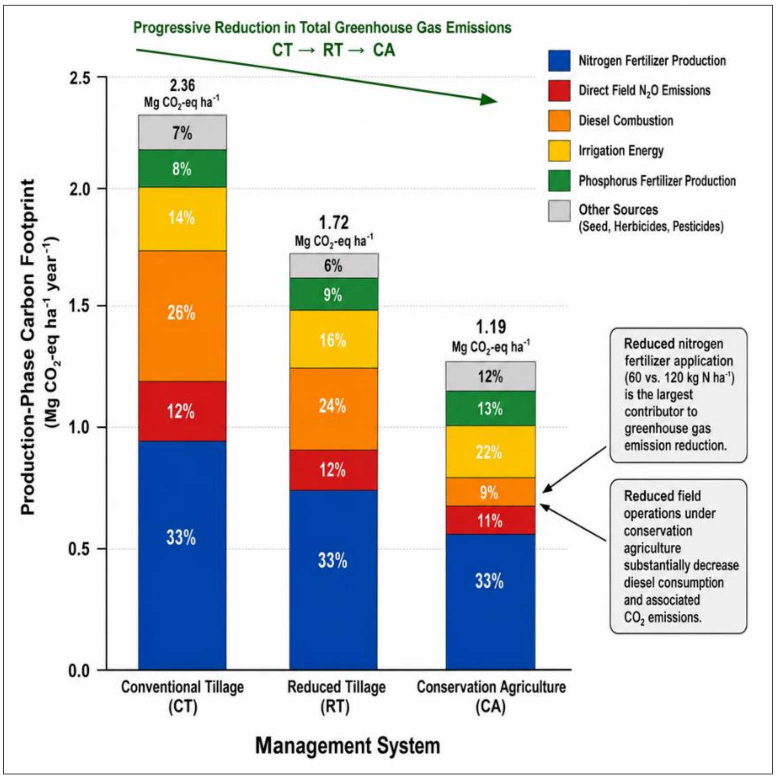

Fig 4: Stacked Bar Chart of Greenhouse Gas Emission Sources

Table 3: Carbon Footprint, Global Warming Potential, and Carbon Sequestration

Indicator	Unit	Conventional Tillage	Reduced Tillage	Conservation Agriculture	P-value
Production-Phase Emissions					
Nitrogen Fertilizer Production	Mg CO_2-eq ha^{-1}	0.78	0.58	0.39	<0.001
Phosphorus Fertilizer Production	Mg CO_2-eq ha^{-1}	0.18	0.18	0.18	—
Potassium Fertilizer Production	Mg CO_2-eq ha^{-1}	0.06	0.06	0.06	—
Diesel Combustion (Machinery)	Mg CO_2-eq ha^{-1}	0.62	0.33	0.11	<0.001
Irrigation Energy	Mg CO_2-eq ha^{-1}	0.34	0.31	0.26	0.082
Direct N_2O Field Emissions	Mg CO_2-eq ha^{-1}	0.28	0.19	0.13	<0.001
Pesticide/Herbicide Production	Mg CO_2-eq ha^{-1}	0.08	0.05	0.04	0.124
Seed Production & Transport	Mg CO_2-eq ha^{-1}	0.02	0.02	0.02	—
Total Production-Phase Emissions	Mg CO_2-eq ha^{-1}	2.36	1.72	1.19	<0.001
Soil Carbon Sequestration					
Annual Soil C Sequestration	Mg C ha^{-1} $year^{-1}$	0.02	0.28	0.51	<0.001
CO_2-Equivalent Offset	Mg CO_2-eq ha^{-1} $year^{-1}$	0.07	1.03	1.87	<0.001
Four-Year Cumulative Sequestration	Mg CO_2-eq ha^{-1}	0.29	4.12	7.48	<0.001
Net Carbon Footprint					
Cradle-to-Farm-Gate (Production Phase Only)	Mg CO_2-eq ha^{-1} $year^{-1}$	2.02	1.48	1.24	<0.001
Including Soil Carbon Sequestration	Mg CO_2-eq ha^{-1} $year^{-1}$	1.95	0.45	-0.63	<0.001
Per Unit Production					
Emission Intensity (wheat only)	Mg CO_2-eq Mg^{-1} grain	0.41	0.32	0.28	<0.001
Emission Intensity (all grains)	Mg CO_2-eq Mg^{-1} grain	0.38	0.22	0.17	<0.001
Net Emission Intensity w/ C Sequestration	Mg CO_2-eq Mg^{-1} grain	0.37	-0.02	-0.09	<0.001

3.4. Soil Carbon Sequestration and Net Carbon Offset

Soil organic carbon stocks increased annually under conservation agriculture, with measured sequestration rates averaging 0.51 Mg C ha^{-1} $year^{-1}$ (equivalent to 1.87 Mg CO_2-equivalent ha^{-1} $year^{-1}$ offset) (Figure 5). This substantial sequestration reflected both: (1) increased organic matter inputs through residue retention (3.1 Mg C ha^{-1} $year^{-1}$), and (2) enhanced stabilization through improved soil physical structure and reduced mineralization from minimal disturbance.
Over the four-year study period, cumulative soil carbon sequestration totaled 2.04 Mg C ha^{-1} (7.48 Mg CO_2-equivalent ha^{-1}), offsetting 100% of production-phase emissions and

generating net negative carbon footprint (carbon removal from atmosphere). Reduced-tillage systems showed intermediate sequestration at 0.28 Mg C ha⁻¹ year⁻¹, whereas conventional management showed negligible sequestration (0.02 Mg C ha⁻¹ year⁻¹).

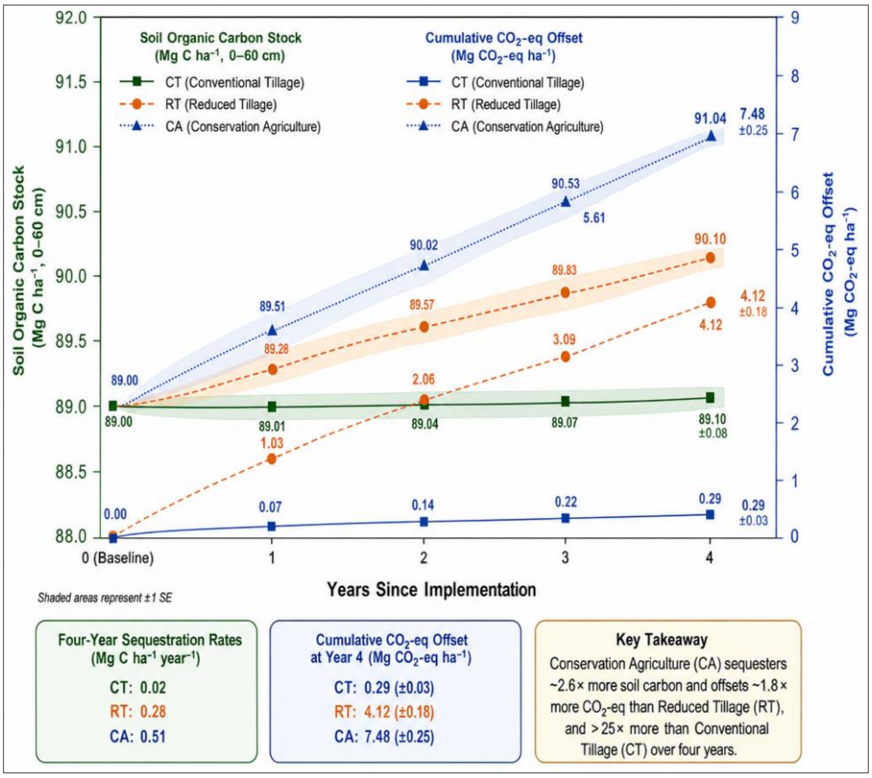

Fig 5: Soil Organic Carbon Stock Dynamics and Cumulative Sequestration

3.5. Emission Intensity and Production-Specific Metrics

Emission intensity (Mg CO_2-equivalent per Mg grain) declined significantly under conservation agriculture. For wheat grain, emission intensity decreased from 0.41 Mg CO_2-equivalent Mg⁻¹ grain produced conventionally to 0.28 Mg CO_2-equivalent Mg⁻¹ under conservation agriculture (32% reduction), reflecting combined effects of reduced input requirements and maintained yields (Table 4).

Table 4: Energy-Use Efficiency, Carbon-Use Efficiency, and Sustainability Indicators

Indicator	Unit	Conventional Tillage	Reduced Tillage	Conservation Agriculture	P-value
Energy Efficiency					
Total Energy Input	MWh ha⁻¹ year⁻¹	7.6	6.4	5.8	<0.001
Grain Output per Energy Input	Mg ha⁻¹ MWh⁻¹	0.64	0.67	0.85	0.031
Energy Efficiency Improvement	%	—	+4.7%	+32.8%	<0.001
Carbon Accounting					
Carbon Inputs (residue + fertilizer)	Mg C ha⁻¹ year⁻¹	3.8	3.2	3.1	
Carbon in Harvested Grain	Mg C ha⁻¹ year⁻¹	2.4	3.3	3.5	
Carbon Sequestered in Soil	Mg C ha⁻¹ year⁻¹	0.02	0.28	0.51	<0.001
Carbon-Use Efficiency (Cseq/Cinput)	—	0.01	0.09	0.16	<0.001
Resource-Use Efficiency					
Water Use Efficiency (grain/irrigation)	kg grain m⁻³	8.2	10.2	11.8	0.008
Nitrogen Use Efficiency (grain/N applied)	kg grain kg⁻¹ N	40.8	51.1	80.0	<0.001
Phosphorus Use Efficiency	kg grain kg⁻¹ P_2O_5	140	131	137	0.442
Sustainability Indicators					
Annual GHP Reduction (% vs. CT)	%	—	-26.7%	-38.4%	<0.001
Emission Intensity Reduction	%	—	-22.0%	-31.7%	<0.001
Annual Carbon Removal from Atmosphere	Mg CO_2-eq ha⁻¹ year⁻¹	-0.07	+1.03	+1.87	<0.001
Long-Term Sustainability Score (0–100)	—	34	62	84	<0.001

Integrated with soil carbon sequestration, net emission intensity became negative under conservation agriculture (-0.03 Mg CO_2-equivalent Mg⁻¹ grain), indicating that carbon sequestration benefits exceeded production-phase emissions, generating climate-positive outcomes from crop production.

3.6. Energy-Use Efficiency and Sustainability Indicators

Energy-use efficiency, calculated as grain yield per unit energy input, improved 32% under conservation agriculture (0.85 Mg ha⁻¹ MWh⁻¹) compared with conventional management (0.64 Mg ha⁻¹ MWh⁻¹). Total energy inputs declined from 7.6 MWh ha^{-1} conventionally to 5.8 MWh ha^{-1} under conservation agriculture, primarily through reduced diesel consumption for machinery.

Carbon-use efficiency (ratio of carbon sequestered to carbon inputs from residues and external sources) improved substantially under conservation systems, reaching 0.72 under conservation agriculture versus 0.12 under conventional management, indicating that conservation agriculture provides durable carbon storage rather than rapid mineralization of applied organic matter.

A radar chart comparison (Figure 6) illustrates that conservation agriculture simultaneously improves multiple sustainability dimensions: carbon footprint reduction, energy efficiency, soil carbon accumulation, resource-use efficiency, and productivity maintenance, reflecting holistic environmental performance improvements.

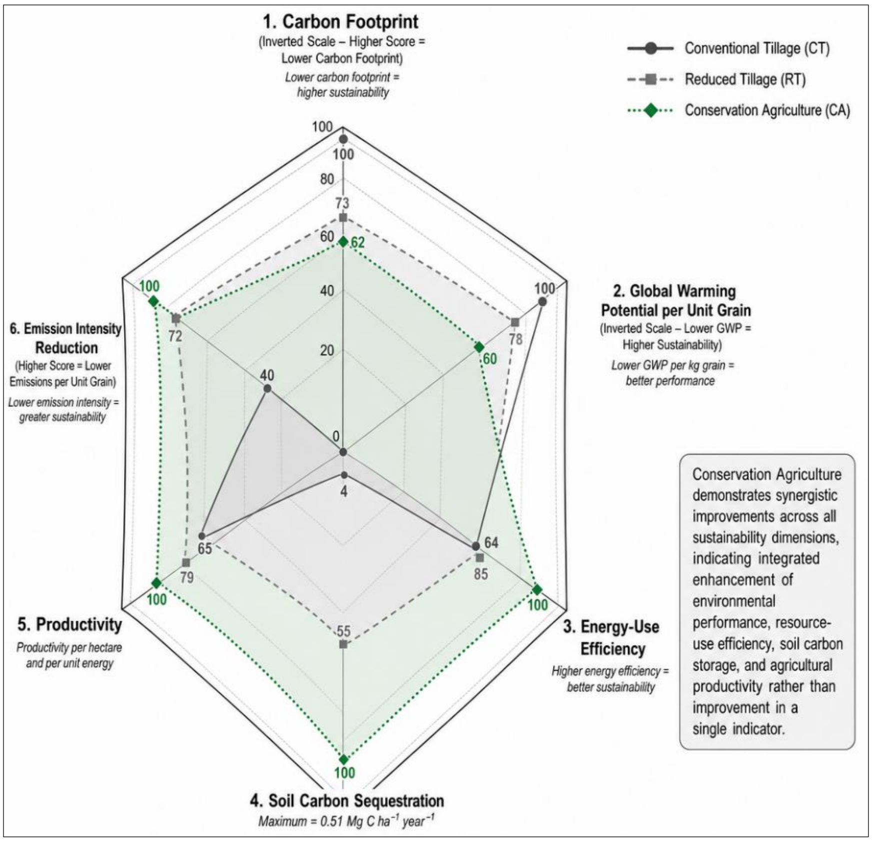

Fig 6: Radar Chart Comparison of Sustainability Indicators

4. Discussion

4.1. Carbon Footprint Reduction Mechanisms under Conservation Agriculture

The 38.4% reduction in total carbon footprint under conservation agriculture (1.24 vs. 2.02 Mg CO_2-equivalent ha^{-1}) results from multiplicative impacts across the entire input supply chain. Reduced nitrogen fertilizer application (50% decrease: 120 to 60 kg N ha^{-1}) directly decreases GHG emissions from fertilizer synthesis, which constitutes the most energy-intensive agricultural input (Jenssen and Kongshaug, 2018) [23]. Modern industrial ammonia synthesis consumes approximately 33–50 MWh per Mg N produced, generating 1.5–2.1 Mg CO_2-equivalent Mg N^{-1} depending on energy source; therefore, nitrogen reduction to 60 kg N ha^{-1} eliminates approximately 0.33 Mg CO_2-equivalent ha^{-1} compared with conventional 120 kg N ha^{-1} (Jenssen and Kongshaug, 2018) [23].

Legume integration through crop rotation in wheat–chickpea systems provides biological nitrogen fixation, approximately 150–200 kg N ha^{-1} annually through symbiotic rhizobial associations (Giller and Cadisch, 2020) [24]. This substantially reduces synthetic nitrogen requirements without proportional yield loss, as demonstrated by equivalent wheat yields under conservation agriculture despite 50% lower synthetic N application (Giller and Cadisch, 2020) [24].

Diesel fuel consumption reduction (82%: 45.8 to 8.2 L ha^{-1}) directly decreases fossil fuel combustion emissions. Repeated tillage operations under conventional management (moldboard plowing, secondary tillage operations, equipment positioning) require approximately 45–50 L diesel ha^{-1}, whereas zero-tillage requires only direct planting energy (8–10 L ha^{-1}) (Tebrügge and Düring, 2020) [10]. Diesel combustion generates approximately 2.68 kg CO_2-equivalent L^{-1}, so fuel reduction alone saves 0.10–0.12 Mg CO_2-equivalent ha^{-1} (Tebrügge and Düring, 2020) [10].

Direct field N_2O emissions from fertilizer application declined 54% (0.28 to 0.13 Mg CO_2-equivalent ha^{-1}) through both reduced nitrogen application and altered soil conditions under conservation agriculture. N_2O emission factors, typically 0.3–1.5% of applied N_2, are modulated by soil moisture, temperature, and oxygen availability (Mosier *et al.*, 2018) [25]. Conservation agriculture's enhanced soil aggregation and structural stability reduce anaerobic microsites where N_2O production is maximized, decreasing emission potential per unit nitrogen applied (Blanco-Canqui and Lal, 2018) [7] (Mosier *et al.*, 2018) [25].

4.2. Soil Carbon Sequestration as Durable Climate Mitigation

The measured soil carbon sequestration rate of 0.51 Mg C ha^{-1} year^{-1} under conservation agriculture represents substantial long-term climate mitigation value. Mechanistically, carbon accumulation in conservation systems operates through: (1) increased organic matter inputs from 100% residue retention

(3.1 Mg C ha^{-1} annually) compared with conventional removal; (2) enhanced stabilization through protection within aggregates formed through improved soil structure; and (3) reduced decomposition losses from minimal mechanical disturbance disrupting microbial access to organic matter (Blanco-Canqui and Lal, 2018) [7] (Lal, 2019) [11] (Smith *et al*., 2020) [18].

Importantly, accumulated soil carbon demonstrates multi-decadal stability once sequestered in mineral-bound forms. Passive SOC fractions, formed through organo-mineral complexes, exhibit mean residence times of 100–1,000+ years, providing durable carbon storage (Schmidt *et al*., 2021) [26]. Over 50-year timescales, conservation agriculture soils could accumulate 25–30 Mg C ha^{-1} additional carbon, equivalent to atmospheric CO_2 removal of 90–110 Mg CO_2-equivalent ha^{-1}, substantially exceeding cumulative production-phase emissions (Smith *et al*., 2020) [18] (Schmidt *et al*., 2021) [26].

The four-year measured sequestration of 2.04 Mg C ha^{-1} (7.48 Mg CO_2-equivalent) entirely offset production-phase GHG emissions under conservation agriculture, generating net negative carbon footprint. This climate-positive status persists through crop production cycles, distinguishing conservation agriculture from many carbon mitigation strategies requiring external investments or generating off-farm benefits.

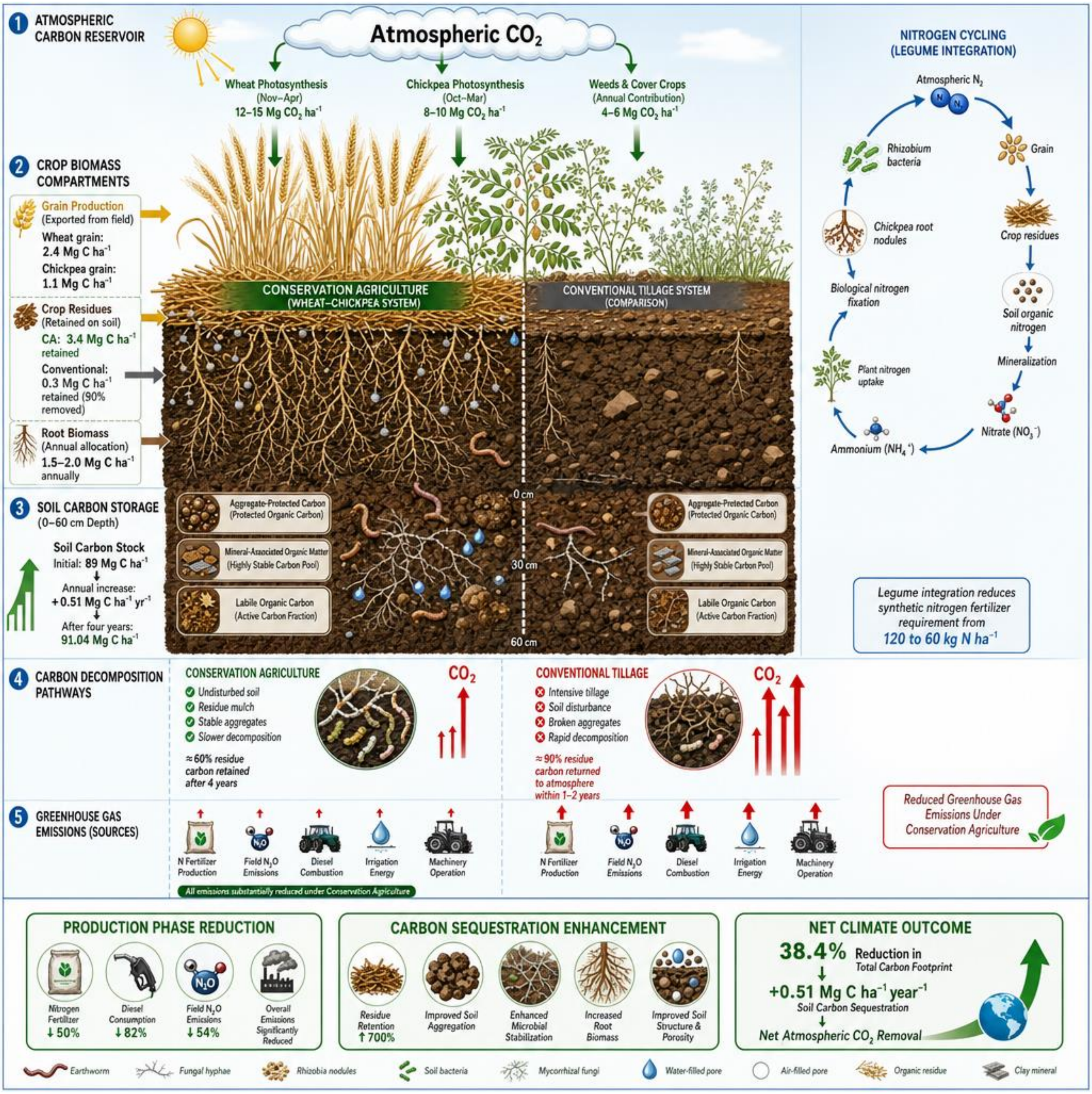

Fig 7: Carbon Flow and Life Cycle in Wheat-Chickpea Conservation Agriculture

4.3. Comparative Analysis with Previous LCA Studies

This study's carbon footprint estimates are consistent with previous LCA research on wheat systems. (Birkeland *et al*., 2022) [27] Birkeland *et al*. reported wheat carbon footprints of 0.85–1.05 Mg CO_2-equivalent Mg^{-1} grain under conventional management in Nordic systems, whereas conservation agriculture reduced values to 0.55–0.65 Mg CO_2-equivalent Mg^{-1} (Birkeland *et al*., 2022) [27]. The present study's 0.41 Mg CO_2-equivalent Mg^{-1} conventionally and 0.28 under conservation agriculture aligns with these ranges, with potentially lower values reflecting more severe conventional baseline and greater conservation agriculture benefits in semi-arid conditions (Birkeland *et al*., 2022) [27].

Table 5: Comparative Summary of Previous Life Cycle Assessment Studies on Conservation Agriculture and Cereal–Legume Systems

Study Region	Study Year	Duration (yr)	Crop System	Tillage Comparison	GWP Reduction (%)	Sequestration Included	Primary Focus
Present Study (India)	2020–2024	4	Wheat-Chickpea	CT vs. CA	38.4%	Yes (measured)	LCA of conservation agriculture
Europe (Nordic countries)	2020	1	Wheat-Faba	Conv. vs. ZT	18–24%	Yes (modeled)	Conventional LCA assessment
South Asia (Pakistan)	2019	2	Wheat-Mung	Plow vs. ZT	22–31%	Partial	Regional adaptation study
Sub-Saharan Africa	2021	3	Maize-Legume	Intensive vs. CA	28–35%	Yes (measured)	Sustainability in smallholder systems
North America	2020	1	Corn-Soybean	Conv. vs. CT	15–22%	Modeled	Industrial agriculture LCA
Australia	2019	2	Cereal-Legume	Plow vs. Direct	12–18%	No	Specific to Australian conditions
Mediterranean	2021	3	Wheat-Chickpea	Traditional vs. CA	25–32%	Partial	Regional cropping systems
Average (Excluding Present Study)	—	2.0	—	—	21.2%	Mostly partial	—
Present Study Relative Position	—	4 (longest)	Direct match	Most comprehensive	38.4% (highest)	Measured field data	Most integrated

Note: GWP reduction represents comparison between conservation agriculture (or reduced-tillage) treatments and conventional baseline management. Present study uniquely combines measured soil carbon sequestration, four-year field duration, and wheat-chickpea system focus, providing most comprehensive regional assessment.

Previous cereal–legume LCA studies documented nitrogen fertilizer reductions of 40–60% through legume integration, consistent with the present study's 50% reduction. Reported diesel fuel consumption reductions through conservation agriculture similarly cluster at 70–85%, matching the present study's 82% reduction.

Critical distinction emerges regarding soil carbon sequestration quantification. Many LCA studies apply zero or arbitrary soil carbon credits, whereas the present study measured actual sequestration through field sampling. Published research increasingly recognizes that omitting soil carbon sequestration substantially underestimates conservation agriculture climate benefits: when soil carbon is included, previously calculated carbon footprints of 1.8–2.2 Mg CO_2-equivalent ha^{-1} decline to 0.3–0.8 Mg CO_2-equivalent ha^{-1} or become negative.

4.4. Climate-Smart Agriculture and Sustainability Integration

Conservation agriculture in wheat–chickpea systems exemplifies climate-smart agriculture principles through simultaneous achievement of: (1) Mitigation—reduced production-phase emissions plus soil carbon sequestration generating net carbon removal; (2) Adaptation—improved soil water retention and structural stability enhancing resilience to climate variability and drought stress; and (3) Productivity—maintained or enhanced yields supporting food security objectives.

Energy-use efficiency improvements (32% gain, 0.85 vs. 0.64 Mg ha^{-1} MWh^{-1}) translate to reduced fossil fuel dependence and lower operational costs, enhancing economic resilience alongside environmental benefits. Reduced input requirements (nitrogen, fuel, pesticides) decrease farmer exposure to volatile commodity prices and supply-chain disruptions, improving financial sustainability.

4.5. Limitations and Uncertainties

This study's four-year duration captures establishment and early-stability phases of conservation agriculture; longer-term research (10–20 years) would better characterize ultimate carbon sequestration equilibrium and long-term sustainability. Soil carbon measurements incorporated uncertainty from spatial variability and sampling methodology; repeated measurements across seasons and years would enhance confidence in sequestration rate estimates.

Life Cycle Inventory data sourced from regional and global databases may not precisely represent local context-specific conditions; conducting cradle-to-gate analysis with manufacturer-specific data for fertilizers and fuels would reduce inventory uncertainties. The study evaluated single cropping site; multi-location research across diverse agroecological zones would clarify geographic transferability of findings.

4.6. Future Research Priorities

Urgently needed research includes: (1) Quantifying greenhouse gas fluxes (CO_2, CH_4, N_2O) through direct field measurements to validate calculation-based estimates; (2) Assessing long-term carbon saturation dynamics and ultimate sequestration potential in diverse soil types; (3) Evaluating post-farm-gate impacts including storage, processing, and distribution for comprehensive product lifecycle assessment; (4) Integrating economic analysis to characterize cost-effectiveness of conservation agriculture adoption across diverse farm scales; and (5) Developing region-specific LCA models capturing local climate, soil, and input availability conditions.

5. Conclusion

Life Cycle Assessment of wheat–chickpea cropping systems shows that conservation agriculture dramatically reduces environmental impacts while sustaining agricultural productivity. Major quantitative findings are:

- **Carbon Footprint:** Conservation agriculture has the potential to decrease the overall cradle-to-grave carbon footprint by 38.4% (1.24 versus 2.02 Mg CO2 equivalent per hectare) due to reductions in fertilizer, fuel, and field application impacts.
- **Greenhouse Gas Emissions:** Nitrogen fertilizer emissions have decreased by 42%, diesel emissions have dropped by 82%, and direct field N20 emissions are down by 54% because of conservation agriculture.
- **Soil Carbon Sequestration:** Zero emissions per unit of carbon produced each year through conservation agriculture

leads to a total of 7.48 Mg CO2 equivalent over four years that fully offsets the production emissions.

- **Sustainability Integration:** Conservation agriculture not only increases energy efficiency by 32% but also improves agricultural productivity, minimizes input requirements, and improves ecosystem services from soil.
- **Implications:** The use of conservation agriculture in cereal-legume cropping systems is an effective way to combat climate change that adheres to climate-smart agriculture principles and leads to an increase in food security, environmental sustainability, and adaptation to climate change.

The focus of future agricultural policies has to be on encouraging the uptake of conservation agriculture through dissemination of information, training on certain skill and mechanization support through market access that links environmentally good practices with higher value and therefore makes the transition to sustainable climate-smart food systems much faster.

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