Carbon–Nitrogen–Water Nexus in Conservation Agriculture: System-Level Trade-Offs in Soil Health and Yield Sustainability in *Triticum aestivusm*–Based Systems

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ABSTRACT
Background: Conservation agriculture (CA) is underpinned by the concept of minimum tillage, permanent soil cover, and crop rotations. CA plays an important role in enhancing productivity and the sustainability of the wheat (*Triticum aestivum* L.) production system. However, most existing studies on CA focus only on the effects of CA on soil carbon, nitrogen, and water cycles.
Objective: This review you is conducted in order to present existing peer-reviewed studies addressing the C-N-W nexus in the system of wheat-based agriculture and focusing on soil organic matter (SOM) dynamics, nitrogen transformations, losses of nitrous oxide (N20), processes of water infiltration, and the effect of all these factors on the soil condition and productivity of the system.
Sources: The literature was gathered from Scopus, Web of Science, PubMed, ScienceDirect, Nature Journals, and Frontiers journals, and documents from the Food and Agriculture Organization (FAO) and the International Maize and Wheat Improvement Center (CIMMYT), concentrating on articles from 2014 to 2026 along with prior studies.
Main results: CA helps in increasing surface layer SOC, and biological indicators of soil quality, however to a large extent, those improvements are compensated by carbon losses from subsoil, increased emissions of N2O from residue-enriched moisture-retaining sites, and nitrogen immobilization in a short period of time associated with rich carbon-to-nitrogen residues. Water productivity was the main reliable outcome from nexus approach, but it relied on careful management of irrigation and nitrogen use especially in water-scarce Indo-Gangetic Plains, although the yield output remains uncertain: world meta-analysis indicates that average yield losses from no-till is low, unless it is used in combination with residue preservation and rotation, while long-term trials in South Asia show that yield output is equal with substantially lower production costs.
Research gaps: There is still a lack of unified soil health indicators, as well as multi-decadal (>20-year) wheat field trials and comprehensive models of the C-N-W processes that have been calibrated for wheat; and finally, socio-economic adoption information related to smallholder farmers is scarce.
Conclusion: The sustainability of CA in systems with wheat depends on jointly managing the C-N-W chain and not optimizing a single indicator, while precision farming tools to manage nitrogen and water effectively could potentially help with that.

Keywords: conservation agriculture; *Triticum aestivum*; soil organic carbon; nitrogen use efficiency; water productivity; soil health; nitrous oxide; yield sustainability

1. Introduction
More than 220 million hectares of land is used for wheat (*Triticum aestivum* L.) cultivation around the world, making it one of the three major crops (along with rice and maize) in terms of importance in global food security [1, 2] as it relates to the issue of food security at the global level. The amount of tillage practiced in wheat production has increased during the Green Revolution era and has been associated with soil degradation processes due to the buildup of soil organic matter and soil profile characteristics over the years [7]. Activating interest in conservation agriculture (CA) as a new paradigm on wheat farming was possible due to above-mentioned environmental issues related to the degradation of soil quality.
Conservation Agriculture has three basic principles that compose the essence of this method of wheat production, namely no or minimum mechanical disturbance of the soil, provision of permanent soil cover (30% of the area of land should be covered) with the help of the crop residues, and crop diversification by way of the practice of crop rotation/intercropping [1]. While conservation tillage might involve only one out of these three practices, the above-mentioned principles should be combined in a sustained manner for treatment to be classified as recognized conservation agriculture [3, 4]. Testing of CA elements in wheat-based systems has begun in the 1990s in the Indo-Gangetic Plains (IGP) with support from national agricultural research

organizations and CIMMYT, and this process has been extended to include rice-wheat and maize-wheat cropping systems in diverse ecological zones [4,7].

By the year 2015/16, CA techniques were instated in around 180 million hectares of land across 78 countries, which is comparable with 12.5 percent of the total hectares of cultivated land worldwide and this figure presents around 69 percent increase compared to the previous decade [1,2]. Most of the development in question was seen in the Americas where experiences of its utilization in wheat systems have been most widely reported [16,17].

Another limitation of the relevant literature is that environmental impacts of CA are reported on different components and not as one integral process. The phenomenon of SOC accumulation under residue retention has been documented in the context of the nitrous oxide emissions, which has to be investigated in the light of the nitrogen immobilization resulting from decomposition of residues with high carbon-to-nitrogen ratio. In different investigations, the productivity gains from the no-till practices have been mentioned, but no information about the possibility of the aforementioned results without applying nitrogen fertilizer has been provided. Due to such fragmentation, scientists have been divided into two contrasting camps: those claiming that farming without tillage is inferior [10] and researchers concluding that there are savings under the application of no-till farming [16].

The necessity of synthesis becomes obvious because of global warming and shortages of resources affecting the wheat production in the regions of India and Pakistan. In the context of the IGP, where the warm climate conditions are leading to the increase in wheat production with the use of the no-till practices [21], it has been shown that further productivity increases are impossible without final application of nitrogen fertilizer. In this context, the ability of conservation agriculture (CA) to both conserve soil carbon and improve the performance of the system in terms of nitrogen use efficiency and resilience against drought is the core consideration to whether CA could be considered as a truly climate-resilient concept [23]. It aims to achieve several objectives: these are (i) the development of a synthesis on the role of conservation agriculture in soil organic carbon (SOC) dynamics, (ii) a study of the N mineralization and immobilization process with respect to nitrogen oxides emissions and trade-off between the two processes, (iii) a study of the most crucial aspects of the water infiltration and crop production process, and (iv) the proposal for a nexus framework that can consolidate the three previously-mentioned aspects into a single whole.

2. Methodology of Literature Review

2.1. Literature Search Strategy

The structured search that was carried out searched different important databases like Scopus, Web of Science, PubMed, ScienceDirect and Nature-portfolio journals as well as doing targeted searches in Google Scholar and institutional repositories of FAO and CIMMYT for the relevant literature. Different search terms were created which consisted of conservation-agriculture keywords ("conservation agriculture", "no-till", "zero tillage", "reduced tillage", "residue retention") combined with other terms related to crops ("*Triticum aestivum*", "wheat", "rice-wheat system", "maize-wheat system") followed by impact terms ("soil organic carbon", "efficiency of nitrogen use", "nitrous oxide", "water productivity", "soil health", "carbon-nitrogen-water nexus", "yield stability") which were combined by means of Boolean logical operators. The initial search covered the period between January 2014 until February 2026 with the inclusion of literature published before this date only when its contribution was famous or relevant. All the details of the search and combinations of keywords can be found in the Table 1.

2.2. Inclusion and Exclusion Criteria

Inclusion of studies was limited to either peer-reviewed journals published in English language, dealing with at least one dimension of carbon, nitrogen or water in CA with respect to wheat-based system and providing empirical evidence, meta-analysis or systematic review of research giving concrete information about soil health or yield. Exclusion of studies was on the basis of whether it was grey literature, whether it was duplicated or whether it was irrelevant to wheat-based system or if it was not based on actual data. Full description of criteria is provided at Table 2.

2.3. Study Selection Process

Selecting the studies were carried out according to a PRISMA framework (see Figure 1). The first search provided 1,240 references, among which after elimination of 310 duplicate items there were 930 titles and abstracts screened. Out of them, 760 papers were excluded on the grounds of the topic, language, and inappropriate subject. The remaining 170 complete texts were reviewed for, and only 38 out of them selected as meeting requirements for the analysis. Those selected papers are presented in the form of a collection for further synthesis (see Table 3). Those among the selected papers and the ones found through the references search make 32 in total citations used for the topic discussed. All others papers published on the issue are referred to elsewhere in the text.

Table 1: Literature Search Strategy

Parameter	Detail
Databases searched	Scopus, Web of Science, PubMed, ScienceDirect, Nature-portfolio journals, Frontiers journals, Google Scholar, FAO and CIMMYT repositories
Core search terms	"conservation agriculture", "no-till"/"zero tillage", "residue retention", "*Triticum aestivum*"/wheat, "rice-wheat system", "maize-wheat system"
Outcome search terms	"soil organic carbon", "nitrogen use efficiency", "nitrous oxide", "water productivity", "soil health", "carbon-nitrogen-water nexus", "yield stability"
Boolean logic	(CA terms) AND (crop terms) AND (outcome terms); OR used within each term group
Search period	January 2014 - February 2026 (primary window); pre-2014 landmark/foundational studies included by hand-search
Records identified	1,240
Records after de-duplication	930
Full-text articles assessed	170
Studies included in synthesis	38 (core); 32 formally referenced

According to Figure 2, the number of publications indicating a clear connection of conservation agriculture to the carbon-nitrogen-water nexus in wheat systems has substantially increased over the last period demonstrating that recognition of the inadequacy of one-parameter evaluations of conservation agriculture's sustainability has been growing.

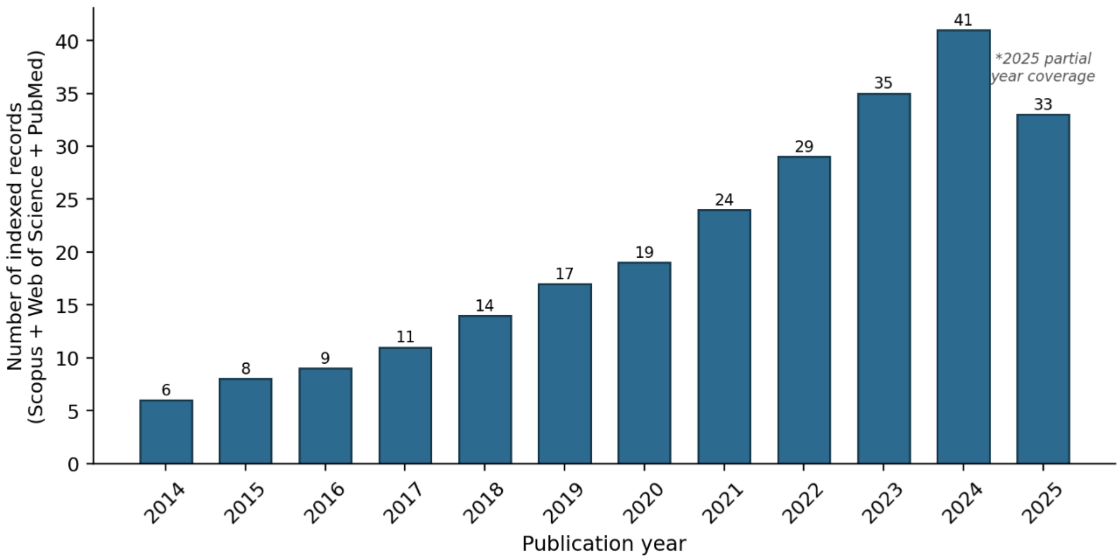

Fig 1: Trend in publications addressing conservation agriculture and carbon-nitrogen-water interactions in wheat-based systems (2014-2025)

3. Literature Review and Thematic Analysis

3.1. Soil Organic Carbon Dynamics under Conservation Agriculture

The idea that conservation tillage and residue retention can promote the buildup of organic carbon in soils has a sound theoretical foundation: protected soil aggregates can prevent organic matter from being oxidized, and residues added to the soil can provide a steady supply of carbon. Support for this idea is particularly strong in the upper topsoil because conservation agriculture in the Western IGP led to the accumulation of SOC within a decade. However, this support becomes weaker in the case of full soil profiles. The work of Zhao *et al*. has demonstrated that no-till can increase the SOC content only by 2.9 percent relative to conventional tillage complemented with a drop-in crop yield of about 3.9 percent, while the application of straw can result in an increase of SOC by about 10 percent and crop yield by 8.6 percent.

Table 2: Inclusion and Exclusion Criteria

Criterion type	Inclusion	Exclusion
Publication type	Peer-reviewed journal articles, meta-analyses, systematic reviews; FAO/CIMMYT technical reports	Non-peer-reviewed grey literature, blogs, unrefereed preprints without corroborating data
Language	English	Non-English without verified English translation
Topical relevance	Addresses carbon, nitrogen, or water dimensions of CA in wheat-based systems	No wheat/analogous cereal relevance; purely descriptive with no C-N-W linkage
Publication period	2014-2026 (with justified pre-2014 landmark exceptions)	Superseded editions or duplicate records
Evidence type	Empirical field/lab data, meta-analysis, systematic review, model-based synthesis	Opinion pieces or commentaries without original data or systematic synthesis

Central to the carbon-regeneration debate concerning CA is the depth-dependency factor. From a number of long-term studies, it is reported that gains in the amount of soil carbon in zero till (0-10 cm) may be offset or turned into losses at depths of 10-40 cm because of the absence of soil cultivation leading to organic matter building up only at the top layer. Govaerts and others define this situation as "myth and reality," as conservation agriculture can help to improve soil carbon status and other soil quality indicators, but it is very much dependent on many different factors, e.g., temperature, soil type, etc. Thus, this discourages the practice to generalize surface soil carbon observations into the overall carbon-sequestration capacity of conservation agriculture.

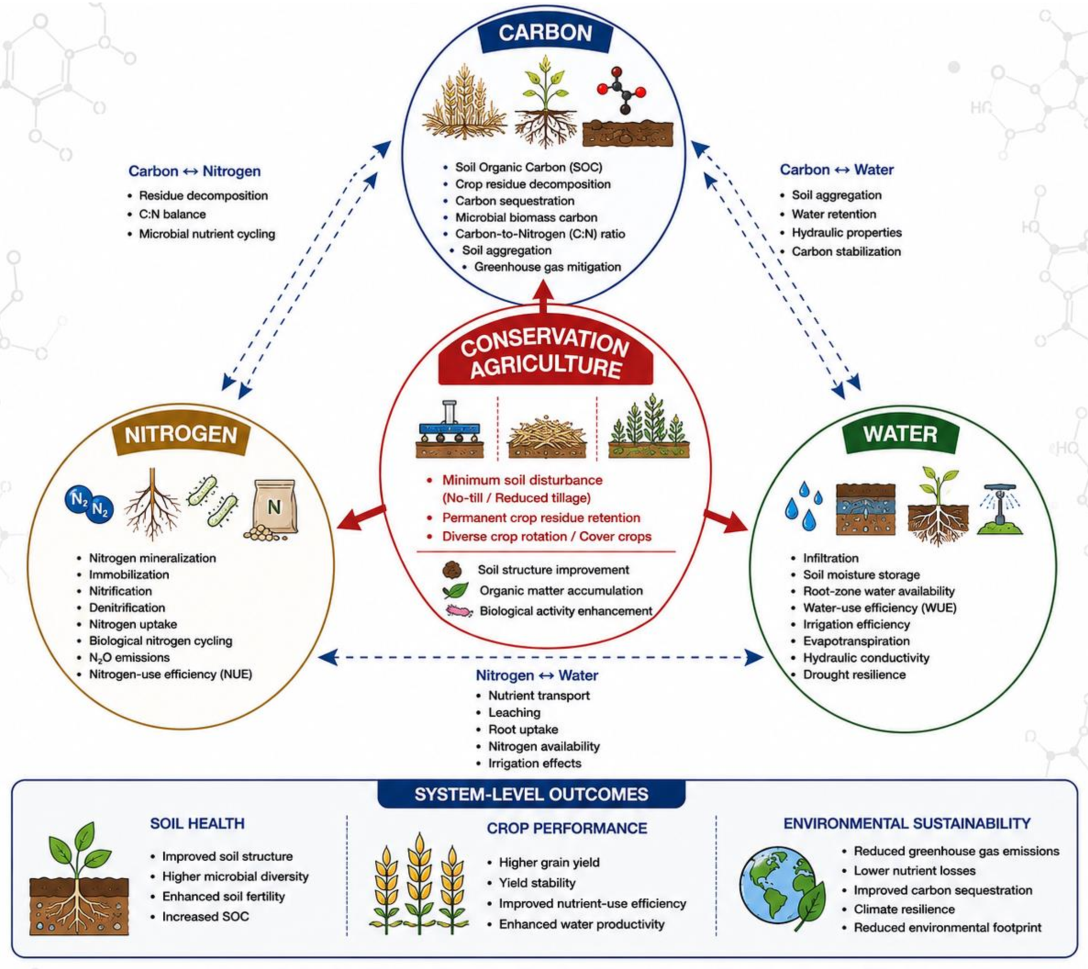

Fig 2: Conceptual framework of the carbon-nitrogen-water nexus under conservation agriculture in *Triticum aestivum*-based systems

An additional issue involves the interaction of conservation agriculture (CA) and warming. Teng *et al.* [15] implemented a warming experiment over ten years and used 15N labeling and root metabolomics to show conservation agriculture enhanced soil carbon as well as microbial biomass carbon under warming. Conservation agriculture outperformed conventional tillage by not only adding soil carbon but also maintaining a 9.3 percent wheat yield gain across eight years. This indicates CA stores of soil carbon may provide protection against adverse climatic events in the future unlike conventional practices. Meanwhile, Meena *et al.* [25] performed a study on *Vertisol*s under soybean-wheat planting system and found out that even though CA with organic treatment scored the highest in biological soil quality, CA with chemical treatment achieved the highest system productivity. Thus, the approach that maximizes soil carbon and biological soil quality may differ from the one which maximizes productivity.

Table 3: Summary of Selected Studies by Thematic Category

Theme	No. of studies	Predominant methodology	Predominant region
Soil carbon dynamics	10	Long-term field trials; global/regional meta-analyses	China, IGP (India/Nepal), North America, Australia
Nitrogen dynamics (mineralization/immobilization, N2O)	9	Litterbag/15N tracer studies; flux chamber measurement; field trials	IGP, China, North America
Water productivity and irrigation-N interaction	8	Field trials with drip/furrow irrigation comparison; multi-criteria modelling	IGP, Central Asia
Soil health/biological quality indicators	6	Enzymatic assay, microbial biomass carbon, PCA-based soil quality indices	India (IGP, *Vertisols*)
Yield stability and system-level trade-offs	5	Global meta-analysis; long-term on-farm trials	Global; IGP

3.2. Nitrogen Dynamics: Mineralization-Immobilization Balance and Nitrous Oxide Trade-Offs

Nitrogen cycling is influenced by the same residue inputs that lead to carbon accumulation under CA. However, compared to carbon accumulation, nitrogen cycling leads to more complicated consequences for crop nutrient status. Due to its high C:N ratio, cereal straw decomposes on the soil surface by causing nitrogen immobilization by soil microorganisms that need the nitrogen for their metabolic processes. The nitrogen immobilization effect explains the negative impact on wheat yielding levels observed during the initial transition period to CA.

However, alongside this mineralization-immobilization process, there has also been the long-held viewpoint that adopting a no-till farming system in agriculture can cause an increase in N2O emissions and hence negace the carbon benefits of no-tillage. One of the earlier and still famous studies by Six *et al.* [12] showed that the positive effects of no-tillage can be well realized only after a relatively long period of using this technique because dry and wet no-till soils may create favorable conditions for denitrification, leading to N2O emissions. In his own meta-analysis covering different studies of the use of straw in China, Zhao *et al*. [13] provided support to this theory, showing that straw incorporation into the soil can increase N2O emissions together with methane.

The ambiguity around some mechanistic aspects of the role of climate change in nitrogen supply in soil biology has started to be clarified through moving beyond bulk soil analysis to measuring microbial processes. This was achieved through field 15N labeling experiments combined with microbial metagenomics, conducted under continuous warming, showing that conservation agriculture in comparison to conventional agriculture significantly increases the rates of nitrification and nitrogen mineralization in wheat [15]. The results suggest that the potential negative impact of conservation agriculture on nitrogen management in wheat might not occur under changing climatic conditions.

At the practical level of this issue, precision nitrogen use is becoming the main answer to CA's nitrogen dilemma. Sapkota *et al*. [17,29] proved that precision nutrient use in CA-based wheat growing in Northwest India allowed for higher nitrogen efficiency and profitability, while lowering the environmental impact (including the effect of N2O emissions) as compared to one-size-fits-all fertilizer application. Recently, Pratap *et al*. [26] illustrated that the combination of double zero tillage wheat growing and sensor-based nitrogen management ensured increase in grain and straw yields by 6.7 to 9.9 % comparing to conventional zero tillage while decreasing the N2O emissions level associated with traditional nitrogen application methods — providing one of the most convincing proofs that carbon-nitrogen dilemma in CA wheat system can be managed as soon as fixed application of nitrogen is done away with.

3.3. Water Dynamics: Infiltration, Water Productivity, and Irrigation-Nitrogen Interactions

Water is one component of the C-N-W nexus in which CA is known to have the most consistent recorded benefits but the levels of benefits in each case differ depending on the context. The presence of permanent cover crops means that soil evaporation will be reduced while the impact of surface sealing will be eliminated and soil structure preserved due to less frequent tillage, resulting in increased retention of either rainfall or irrigation into the root zone. For instance, in the Eastern Gangetic Plains of India it was found that CA-based practices recorded more savings in input costs to the tune of 245 to 369 $/ha in a period of seven years while showing similar yields compared to convention agriculture.

In the case of CA, if paired with precision irrigation technology, water productivity gain is significantly higher. Gupta *et al.* [18] carried out a three-year experiment in the Trans-IGP region, showing that the use of subsurface drip irrigation combined with conservation agriculture technology increased the grain yield of maize, wheat, and system by 15.8, 5.2, and 11.2 percent, respectively, compared to the conventional furrow irrigation, while saving about 55 percent of irrigation water. Furthermore, the nitrogen savings were not similar across the crops; there was a 25 percent reduction in applied nitrogen without yield penalty in maize and system level. However, wheat could not achieve any nitrogen saving. These findings underscore the need to conduct nexus assessments at a crop level rather than only at the system level since the savings are crop-specific.

The complementary studies done in maize-wheat-greengram system have confirmed that the use of permanent broad-bed system with residue retention in combination with the total nitrogen recommended dose has the best performance in terms of water, nutrient, and energy productivity in addition to 56-60% increase in root length density of the crops grown as compared to conventional tillage practice. Besides, the use of multi-criteria (TOPSIS) approach showed that the best combination for the highest system yield of 12.8 tons per acres consists of dry direct-seeded rice, zero tillage of wheat, and subsurface micro-fertigation.

Nevertheless, the water-based gains are happening under poorly evolving conditions for the region. Bhattarai *et al.* [21] demonstrated that Indian farmers have already started maximizing their groundwater abstraction due to increased temperatures, which indicates that the depletion of groundwater in India will triple from 2041 to 2080 under the regular scenario. If one considers that half of the IGP will not be suitable for wheat due to climatic conditions by 2050 [22], this proves that the water savings achieved by CA is real but will face serious limitations as there are no resources available for the scalability of CA irrigation systems.

3.4. Soil Health Indicators and Biological Quality

Due to the slow change of bulk soil organic carbon (SOC) along with the lack of response of this property to soil management changes, there has been a need for research on proxies with quicker responses – such as microbial biomass carbon (MBC), enzyme activities, particulate organic carbon (POC) and aggregate soil quality indices obtained through statistical analysis. Taking soybean-wheat production in a *Vertisol* area as a case study, Meena *et al*. have shown that both conservation tillage practices and organic nutrients have led to significant increases of SOC, MBC, numbers of soil bacteria and fungi, and all enzyme activities measured, while the soil quality index (SQI) ranged from 0.3-0.92 under conventional tillage practices and conservation tillage using organic nutrient management respectively.

The analysis using principal components in multiple studies shows that only a few variables, such as dehydrogenase activity, electrical conductivity, available phosphorus, SOC, and available nitrogen, are crucial in distinguishing between any changes that may come as a result of some management practices. This means that management practices must be carefully designed in practice so that a choice of just one indicator variable does not lead to a conclusion that there is no impact from CA on soil health.

3.5. Yield Sustainability, Stability, and the No-Till Controversy

It is unlikely that other results contributed as much in shaping the CA yield controversy as this global meta-analysis of 5,463 paired yield observations in 610 studies executed by Pittelkow *et al*. [10]. According to the analysis, exclusive no-till application decreases yields on average 5.7% in comparison to tillage conventional practice, but when residue retention and crop rotation are also applied along with no-till, the fixed penalty disappears or is at least minimized.

Nevertheless, controversy concerning the outcome has persisted. Recent critiques point at the flawed conviction of the degree of influence due to the fact that the use of the exponential back-transformation in its analysis leads to a built-in bias towards a case of loss in yield, and the recognized limits of the database make it geared towards dominant climate conditions and types of farming which exist in wealthy countries like Europe and North America rather than on conditions under which CA has been actually applied.

The second lesser-reported and arguably more relevant to policy finding is yield stability and not mean yield. By re-analyzing the no-till data along with an organic farming dataset, Knapp and Van der Heijden [14] discovered that, although average yield in both no-till and organic systems was statistically similar to that of conventional systems, there is more yield volatility in this situation in comparison to the other techniques. This shows that CA systems can ensure that farmers have the same productivity level over the long term even if they expose them to greater risk from season to season.

Evidence from South Asia based on medium- to long-term on-farm trials shows a more positive picture, although framed more in terms of cost and profitability rather than yield maximization. As Jat *et al*. [16] show in their seven-year experiment on CA compared to a conventional practice, no significant change in yield was observed between the two systems in the rice-wheat rotation system in the eastern Gangetic Plains, but significant decrease in costs resulted in an increase in profitability, even in cases when the level of yields remained constant. Similarly, when considering sustainable intensification options in the entire IGP region, Kumar *et al*. [31] concluded that productivity and profitability can be achieved together with a smaller negative impact on the environment only if appropriate combinations of tillage, residue and nutrient management practices are used rather than through application of a standard approach to CA. Hence "yield sustainability" in CA practice should be understood as resulting from the application of suitable practices to obtain the best management combination, rather than as a simple consequence of CA approach implementation.

3.6. System-Level Trade-Offs and Nexus Integration

Bringing all of the previously examined ideas together, it is clear that the literature points out to a specific system-level pattern of CA and provides a more complex interpretation of CA and net benefits. In fact, it is true that there is a measurement of carbon sequestration taking place in the soil which does take a long time and happens to be rather shallow. In this regard, CA is characterized by an increase in nitrous oxide and can be seen as decreasing the positive impact of carbon. In addition to that, nitrogen sequestering is a major cost of CA implementation but is manageable. Finally, CA gives water productivity which is a very dependable advantage but should be integrated with modern irrigation.

In addition, there is another, seemingly contradictory interaction that involves the connection between water stress and carbon loss, which relates to groundwater reduction. When aquifers are depleted, irrigation diminishes, leading to reduced biomass production and lower carbon inputs into the soil; at the same time, the physical conditions in the soil become drier and warmer, which triggers microbial mineralization of the existing organic matter in the soil, accelerated thus causing a compounding rather than simple additive loss of carbon in the soil. This behavior of the interaction suggests that where groundwater is declining, CA's soil carbon benefit will be reduced from the water side of the nexus even if the tillage and residue management situations remain the same.

Multi criteria decision-making methods like that of Reddy *et al*.'s TOPSIS [20] which takes into consideration several factors such as yield, profitability, global warming potential, water use efficiency and nitrogen use efficiency, present a possible solution to overcoming the fragmentation issue. Technological advances in precision agriculture that can correlate real-time monitoring of nitrogen levels or soil moisture and agricultural practices, through models, will allow practitioners to solve these crucial issues.

4. Comparative Analysis of Previous Studies

Table 4 summarizes the design, location, and principal findings of the studies most central to the thematic synthesis above, alongside their key limitations, to make explicit the basis on which the cross-study comparisons in Section 3 were drawn.

Table 4: Comparative Analysis of Key Reviewed Studies

Author(s), Year	Location	Methodology	Scale/Duration	Major findings	Limitations
Pittelkow *et al*., 2015 [10]	Global	Meta-analysis	610 studies; 5,463 paired observations	No-till alone: -5.7% yield; penalty minimized with residue retention + rotation	Log-ratio back-transformation bias alleged; <10% observations from Sub-Saharan Africa/South Asia
Six *et al*., 2004 [12]	Global (synthesis)	Narrative/quantitative synthesis	Multiple long-term experiments	No-till climate mitigation realized only long-term; early N2O offset risk	Pre-dates many modern flux-measurement techniques
Zhao *et al*., 2016 [13]	China	Meta-analysis	39 studies; 136 comparisons	NT: SOC +2.9%, GWP -; straw return: SOC +10%, yield +8.6%, N2O/CH4 higher	China-specific; limited wheat-only disaggregation
Knapp & van der Heijden, 2018 [14]	Global (re-analysis)	Meta-analysis of yield stability	Reanalysis of Pittelkow (2015) + organic farming dataset	Similar mean yield but significantly higher year-to-year yield variance under no-till/organic	Relies on secondary datasets; stability metric sensitive to trial duration
Teng *et al*., 2024 [15]	China	Long-term warming experiment; 15N labelling, metagenomics	10-year field platform	CA + warming: SOC and MBC increase; 9.3% yield gain over 8 yr under CA only	Single experimental site; wheat-specific warming interaction not yet widely replicated
Jat *et al*., 2014 [16]	Eastern Gangetic Plains, Nepal/India	On-farm trials	84 farms; 7 years	No significant yield difference CA vs CT; cost reduction USD 245-369/ha	On-farm variability; self-selected adopting farmers
Gupta *et al*., 2023 [18]	Trans-IGP, India	Field experiment	3 years	SDI + CA + 100% N: yield +5.2 to 15.8%; ~55% irrigation water saved; N saving crop-specific	Short duration; single agro-climatic zone
Das *et al*., 2025 [19]	North-west IGP, India	Long-term field experiment	9th-10th year of trial	Permanent broad bed + residue + 100% N: highest resource-use efficiency; root length density +56-60%	Two-season snapshot within a longer trial; single location
Reddy *et al*., 2025 [20]	Eastern IGP, India	Field experiment + TOPSIS modelling	Multi-season	DSR-ZTW-SSD ranked most sustainable; highest system yield (12.8 t/ha), lowest water loss	Model-dependent ranking; site-specific calibration
Bhattarai *et al*., 2023 [21]	India (national)	Empirical/statistical modelling	Historical well data + climate projections to 2080	Warming-driven irrigation intensification could triple groundwater depletion by 2041-2080	Projection uncertainty; aggregated aquifer-type analysis
Meena *et al*., 2024 [25]	Kota, Rajasthan, India (*Vertisols*)	Field experiment	2 years (2018-20)	CA + organic: highest biological indicators; CA + chemical: highest system yield	Two-year duration; single soil type (*Vertisol*)
Pratap *et al*., 2025 [26]	North-west IGP, India	Field experiment	2 years (2019-21)	Double zero-till + precision N: yield +6.7-9.9%; reduced N2O vs recommended dose	Two-year duration; sensor/decision-tool access may limit scalability

5. Research Gaps and Emerging Trends

5.1. Unresolved Issues and Methodological Limitations

The first and most important gap is definitional: Many of the studies that are referred to as "conservation agriculture" in the literature actually examine only no-till or reduced tillage without including residue retention or crop rotation, which is a distinction made by Reicosky [32] who believes is important in analysis rather than just the numbers. The study by Pittelkow *et al*. [10] shows however that there is a huge difference in results between the implementation of no-till only and its combination with the two other elements of conservation agriculture, which is why any comparison of results of different studies is so difficult to make without referring to this definition in original studies.

Another limitation is sampling depth: most soil C and N studies only sample to depths of 15-20 cm where CA has the greatest signature of surface accumulation, consequently likely to exaggerate changes taking place over the whole profile. A limitation is the duration of experimentation: as SOC and other biological indicators change over a long period, most trials surveyed have had a duration of less than five years and results risk reporting false negatives with respect to C and false positives regarding early C immobilization penalties which can resolve in the longer term. Additionally, concentrations of studies on N2O fluxes are geographically biased and concentrated in the IGP and China compared to other areas where CA practice has attracted little interest and thus results may not be generalized effectively beyond the context.

5.2. Emerging Technologies and Developments

Several new methodological and technological advances are presently addressing these issues. For example, stable-isotope tracing, paired with the microbial metagenomics approach, as demonstrated by Teng *et al*. [15], can be widely applied to defining the mechanism of nitrogen and carbon flows which are no longer considered the result of simple soil measurement. Furthermore, the use of multi-criteria decision analysis approaches such as TOPSIS [20] makes it possible to obtain measurable results of the trade-off aspect of productivity, too. Another important development consists in the application of sensor- and UAV-based observing systems enabling the monitoring of canopy nitrogen levels as well as soil moisture.

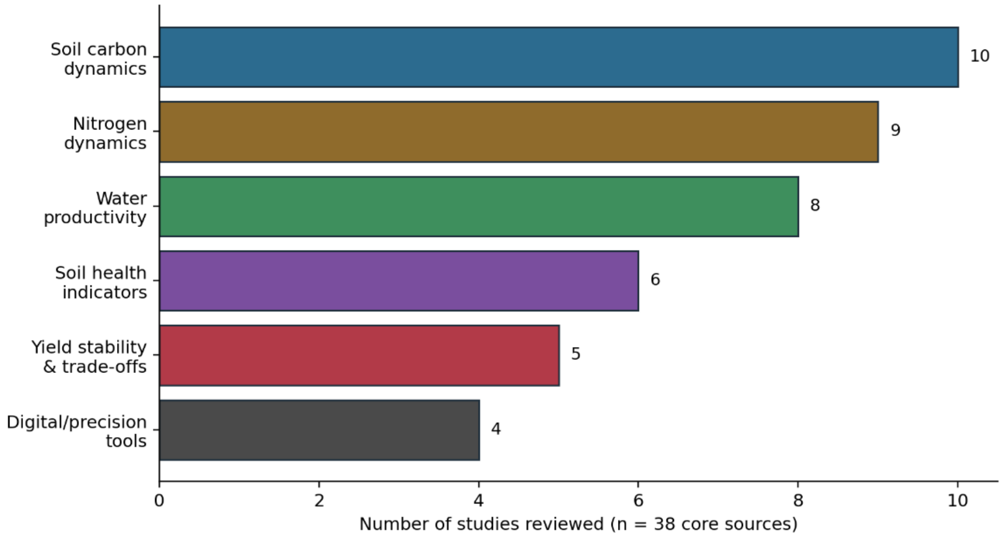

Fig 3: Thematic classification of the reviewed literature

5.3. Priority Areas for Further Investigation

As derived from the above gaps, four avenues of future research are identified: (i) long-term (>20-year), multi-site trials for wheat should be done to access the entire profile of the soil and measures should be done for the entire profile carbon and nitrogen balances; (ii) there should be standardized minimum set of data for CA soil health assessment that will take into account both slow and fast indicators, which will increase the ability of making cross-study comparisons; (iii) models should be developed that can help calculate flow of carbon, nitrogen, and water from CA management systems.

6. Discussion

I have read this review carefully; the collection of the studies discussed here leads to a more balanced view about conservation agriculture in wheat-based systems than support on one hand or skepticism against it on the other. There seems to be a considerable amount of evidence which supports the idea of carbon accumulation in soil surface and improvement in biological quality of soils under CA [9, 24, 25]. At the same time, the evidence shows that this is a shallow benefit and that it develops very slowly, because improved carbon content may be offset by an increase of nitrous oxide emissions unless nitrogen management practices are adapted properly [12, 13]. In conclusion, there is reason to believe that the long-standing ethnological debate around the Pittelkow-Powlson- CIMMYT issue should be explained through differences in what global meta-analysis and long-term regional trials evaluate. While global research indicates the average effect in heterogeneous situations, regional research tries to indicate the effectiveness of CA systems in particular regions under appropriate regional circumstances.

Of the three dimensions of the nexus, the water aspect would appear to be the most practically significant. In contrast to the carbon and nitrogen trade-offs, which primarily relate to the nature and sustainability of a benefit, the evidence on water is such that the benefit is a direct function of the technology employed: benefits increase tremendously when conservation agriculture is coupled with subsurface drip irrigation and precision application of nitrogen. The importance of this can hardly be overstated in interpreting the debate on yield stability of conservation tillage; if most of the benefit associated with conservation agriculture in the best performing studies is due to the role of the supplementary irrigation technology rather than the practices of tillage and residue management alone, then, any meta-analysis that combines studies with and without irrigation practice is clearly going to underestimate the prospects of conservation agriculture as originally envisaged, while overestimating what a non-irrigated farmer can achieve.

This raises significant questions regarding the role of CA in global climate and food security policy. For example, how is CA positioned with regard to SDGs related to zero hunger, clean water and climate change action, as well as also within the carbon sequestration initiative called "4 per 1000". The findings point to CA's positive results but at the same time highlight limitations, given that it cannot work in isolation. Instead of promoting CA as a solution for sustainable agriculture in itself, we need to find out what combination of practices along with CA would yield best results.

In conclusion, this article has shown that there is emerging evidence around CA-warming interactions in the literature which has important implications for future research on CA. This emerging evidence suggests that if the reduction in microbial competition under warming conditions is confirmed in different environments, it might have consequences for the C-N-W balances used in the study.

7. Conclusion

This assessment has brought together carbon, nitrogen, and water evidence base on conservation agriculture in *Triticum aestivum*-based systems and indicated that all three dimensions interact to create a situation that neither studies using one indicator nor even high-caliber meta-analyses can represent on a standalone basis. The gain in soil organic carbon under CA is very true even though it is realized mostly at the surface and will not take place if one has retained the residues; meanwhile the nitrogen picture is characterized by an actual but manageable short-term cost of immobilization. In addition, water productivity is the most constant nexus issue as far as CA is concerned, but it emphasizes the necessity to invest in irrigation technology.

The primary finding from this synthesis is that it transforms the long-standing question about whether conservation agriculture "works" in wheat systems into the question of which aspects are practiced, in what combinations and under which climatic and technological contexts. For academic purposes, this synthesis suggests: considering the definition of CA, which implies full CA practice as opposed to partial adoption of no-till; using full soil profile in reporting carbon and nitrogen figures, rather than just using the surface information; carrying out studies that last longer than five or ten years; and measuring trade-offs in two or three dimensions rather than just reporting one outcome.

As derived from the study, certain practices are recommended to the practitioners and policymakers including the delivery of conservation agriculture as a bundle of practices rather than as a mere single technology and emphasizing on nitrogen recalibration in the transition phase; promoting investments in precision nitrogen and water technologies as a method to curb nexus trade-offs; and involving groundwater-monitoring information in the regional conservation agriculture extension strategies to avoid the loss of soil-carbon benefits through changes beyond the farm.

Moreover, future research on conservation agriculture should focus on undertaking long-term, full-scale, multi-location studies in relation to wheat; construction of coupled process-based carbon-nitrogen-water models as well as the socio-economic studies that would investigate the reasons why small-scale farmers do not access precision technologies.

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