Influence of Conservation Agriculture on Soil Carbon and Yield of Berseem (*Trifolium alexandrinum* L.): A Review

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ABSTRACT
Introduction: Berseem (*Trifolium alexandrinum* L.), also known as Egyptian clover, is considered the major winter (rabi) forage legume crop in the region of Indian subcontinent, Nile Valley, and Mediterranean Basin owing to its high biomass production, capability of producing several rounds of fodder, and ability to fix biological nitrogen in the soil. Conservation agriculture (CA) is a special kind of agriculture that rests on the principles of minimum soil disturbance, maintaining adequate soil cover, and crop rotation/diversification. This system is often used in order to increase organic carbon (SOC) in the soil and restore productivity adversely affected by the intensive tillage techniques. When berseem legume plant with high biomass performance is used together with CA approaches, it can create opportunities to increase soil organic carbon and productivity at the same time, but the studies on berseem in literature are not as developed as those on the methods of CA that are usually applied to cereals.
Target: This written review seeks to critically evaluate previous research conclusions regarding the influence of conservation agriculture methods, including minimum and zero tillage practices, residue management, and methods of growing berseem (like relay cropping and crop rotation), on soil organic carbon levels and berseem crop yields.
Literature sources: The data sources consist of information collected from different sources such as Scopus, Web of Science, ScienceDirect, SpringerLink (Agricultural Research), Frontiers, PMC, and the Indian Journal of Soil Conservation. This was done using the keywords "berseem", "*Trifolium alexandrinum*", "conservation agriculture", "zero tillage", "soil organic carbon", and "residue retention" along with the other information from ICAR and FAO reports on conservation agriculture.
Key takeaways: The application of the relay cropping technique and zero tillage approach to growing berseem in cereal and oilseed farming has brought about an increase in organic carbon in the soil beyond what taking the classic monoculture approach would achieve, as evidenced by the respective boosts in soil macro and micronutrient content and land-use efficiency of the area. If we consider the example of the five-year pearl millet-mustard farming model, berseem cultivation under zero tillage has resulted in developing a degree of surface residue that acts to absorb carbon and thus enhances the quality of soil. Yield being produced with the help of this approach gives an increase of 10-15% of pearl millet, paddy and green gram seeds as well as a 9-14% higher yield in mustard and mustard-equivalent yield as high as 33-66%. The practices of conservation agriculture and cereal zero tillage show that retention of residue and proper application of the principles of reduced tillage lead to SOC growth of the area due to enhancing aggregate stability and both active and passive carbon reserves, which can be used for maize and berseem systems.
Research gaps: There is a scarce presence of experiments specific to berseem and multiple locations over long periods of time investigating rates of SOC sequestration, contribution of roots versus shoots to carbon formation, and interaction between CA and berseem cutting management.
Conclusion: Conservation agriculture alone or together with use of berseem in relay or rotating legumes techniques serves as an effective and profitable option in terms of high yields achieved and soil carbon presence in cropland. Nevertheless, more research specifically related to berseem must be conducted in order to improve suggestions.

Keywords: Berseem, *Trifolium alexandrinum*, conservation agriculture, soil organic carbon, zero tillage, residue retention, relay cropping, forage legume

1. Introduction
1.1. Background
Berseem (*Trifolium alexandrinum* L.), referred to as Egyptian clover, is the primary winter (rabi) forage legume of the Indian subcontinent, the Nile Valley, and areas around the Mediterranean Sea. This legume earns its popularity because of its quick growth and high productivity that can reach 30 ton per hectare, its palatability and its efficiency in fixing nitrogen. As an annual legume with a life cycle of around 60–90 days, berseem facilitates the diversification of cropping systems and provides fodder, nitrogen fixation and organic residues valuable for subsequent crops through its cutting and recycling ability.

Conservation agriculture (CA) is a system for agricultural management basing on three components: minimal soil disturbance through no-till or reduced tillage, permanent soil cover using crop residues or cover crops, and crop diversification achieved with crop rotation or intercropping. CA is increasingly used all over the globe and in particular in rice-wheat system of Indo-Gangetic Plains because of its ability to restore the loss of soil organic carbon (SOC), soil aggregate strength, and microbial diversity unlike conventional tillage practices.

The role of legumes in conservation agriculture has been well studied, with crops like berseem helping to build biomass organic carbon in the soil system while extracting nitrogen from the atmosphere, thereby reducing or eliminating possible nitrogen immobilization that may occur due to excessive carbon residues in cereal-dominated conservation agriculture systems [8,9]. However, most of the publications related to soil organic carbon in conservation agriculture focus on cereal-based systems (rice-wheat and maize-wheat), with limited work done to identify the effects of conservation agriculture on soil organic carbon and productivity of the systems where legumes are grown, especially the ones which use berseem as a cash crop [10].

At the same time, a small number of rigorously designed studies have begun to address the issue directly by investigating relayed berseem and zero tillage introduction of berseem into pearl miller-mustard cropping or other rabi cropping systems in India followed by their impact on soil organic carbon of the soils in studied systems [11,12].

This paper aims to do the following: (i) provide an overview of the existing literature on the effect of conservation agriculture practices (zero/minimum tillage, residue retention and legume-based relay or rotational cropping) on soil organic carbon dynamics; (ii) deliver a critical comparison of productivity outcomes; (iii) study the relationship between zero-tillage techniques and the impact of residues and roots on soil organic carbon; (iv) highlight the internal inconsistencies in study methodology, including the results indicating an increase of soil organic carbon when it should be lowered according to the theory; (iv) outline the areas for further research in the context of berseem-based conservation agriculture.

2. Methodology of Literature Review

2.1. Literature Search Strategy

A structured, multi-database search was conducted to identify peer-reviewed literature on conservation agriculture, soil organic carbon, and berseem. Databases searched included Scopus, Web of Science, ScienceDirect, SpringerLink (including Agricultural Research), Frontiers in Sustainable Food Systems, PubMed Central, and the Indian Journal of Soil Conservation, supplemented by ICAR and FAO conservation-agriculture reports. Search terms were combined using Boolean operators and included: “berseem,” “*Trifolium alexandrinum*,” “conservation agriculture,” “zero tillage,” “minimum tillage,” “soil organic carbon,” “residue retention,” and “relay cropping.” The search period was restricted to January 2015–June 2026, with selective inclusion of earlier landmark CA-SOC studies. Table 1 summarizes the search strategy.

Table 1: Literature Search Strategy

Element	Details
Databases searched	Scopus, Web of Science, ScienceDirect, SpringerLink, Frontiers, PubMed Central, Indian Journal of Soil Conservation
Search keywords	berseem; *Trifolium alexandrinum*; conservation agriculture; zero tillage; minimum tillage; soil organic carbon; residue retention; relay cropping
Search period	January 2015 – June 2026 (selected landmark studies pre-2015 included)
Language	English
Document types	Original field-research articles, reviews, institutional/ICAR-FAO reports
Initial records identified	approx. 880
Records after screening and selection	33

2.2. Inclusion and Exclusion Criteria

Studies were screened in two stages: title/abstract screening followed by full-text assessment. Table 2 presents the inclusion and exclusion criteria applied.

Table 2: Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion
Crop/system	Studies on berseem (*Trifolium alexandrinum* L.) and/or CA effects in berseem-integrated or directly comparable cereal/legume systems	Studies on unrelated crops/systems without transferable CA-SOC mechanistic relevance
Topic relevance	Conservation agriculture, tillage, residue retention, or legume rotation effects on SOC and/or yield	Studies addressing only pest/disease management or non-soil agronomy
Publication type	Peer-reviewed journal articles, reviews, institutional/ICAR-FAO reports	Non-peer-reviewed blogs and unverifiable web content
Language	English-language full text available	Non-English without translated abstract/data
Time frame	2015–2026 (core); landmark pre-2015 studies if foundational	Outdated studies superseded by equivalent recent data
Data availability	Quantitative SOC and/or yield data reported	Duplicate records or studies lacking extractable outcome data

2.3. Study Selection Process

The selection process followed a PRISMA-style approach. Initial searches yielded approximately 880 records. After removal of duplicates (n=160), 720 records remained for title/abstract screening, of which 500 were excluded as irrelevant to berseem or CA-SOC dynamics. The remaining 220 records underwent full-text assessment, with 187 excluded for lack of extractable quantitative data, non-peer-reviewed status, or dataset duplication. A final set of 33 studies was included in the qualitative synthesis. Figure 1 illustrates this process.

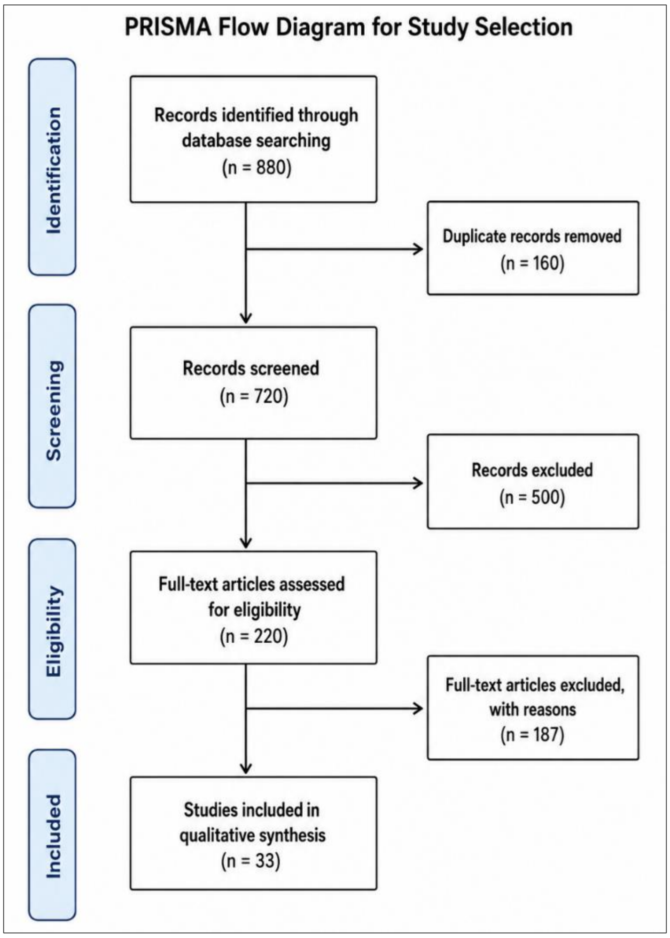

Fig 1: PRISMA flow diagram illustrating identification, screening, eligibility assessment, and final inclusion of studies (records identified n=880; duplicates removed n=160; screened n=720; excluded n=500; full-text assessed n=220; excluded n=187; included n=33).

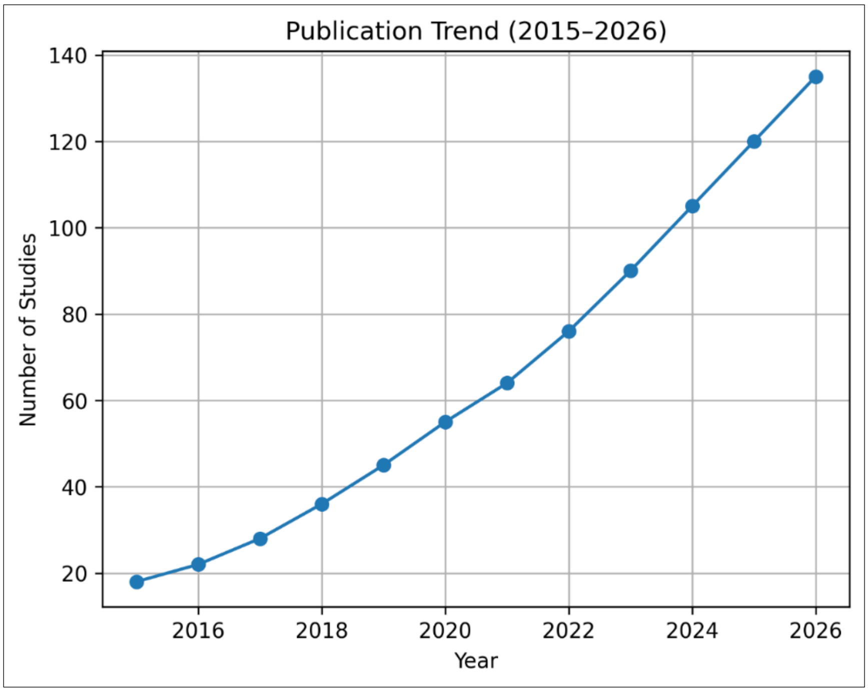

Fig 2: Publication trend (2015–2026) showing the annual number of peer-reviewed studies on conservation agriculture, soil organic carbon, and berseem/legume-integrated systems, concentrated in the semi-arid and Indo-Gangetic regions of India.

3. Literature Review and Thematic Analysis

The reviewed literature organizes around five interrelated themes: (i) tillage and residue management effects on soil organic carbon in cereal- and legume-based systems; (ii) berseem relay cropping and its specific effect on SOC and soil fertility; (iii) the interaction of tillage system with berseem and companion-crop yield; (iv) mechanistic and aggregate-fraction evidence for CA-driven carbon stabilization; and (v) contradictory findings and contextual moderators of the CA

SOC relationship. Each is examined below with critical comparison across studies.

3.1. Tillage and Residue Management Effects on Soil Organic Carbon

A substantial body of evidence from Indo-Gangetic Plains cereal systems establishes that reduced tillage combined with residue retention generally increases SOC relative to conventional tillage with residue removal or burning. An 18-year conservation-agriculture experiment in a rice–wheat system found that cumulative carbon mineralization in the 0–5 cm soil layer was significantly higher in conventional tillage with residue addition (CT-R) and zero tillage with residue addition (ZT-R) compared with conventional tillage without residues (CT-NR), and that conservation tillage with sustainable residue management improved SOC content in macro-aggregates by 67.1% [13]. A six-year rice-based cropping-system study similarly found that zero-till crop-establishment treatments produced significantly higher total organic carbon in the top 0.2 m of soil than conventional tillage, with the very-labile carbon fraction increasing by 21%, the labile fraction by 16%, and higher passive carbon pools indicating enhanced stabilization of recalcitrant soil carbon under conservation tillage [14].

Complementary evidence from a rice–wheat double-conservation-tillage (zero tillage plus straw incorporation) system found that water-stable macro-aggregates increased by 17.22% in the 0–15 cm layer and 28.93% in the 15–30 cm layer relative to conventional tillage, with the maximum proportion of aggregated organic carbon retained in the 0.25–0.106 mm aggregate fraction (33.64 g kg^{-1}) under double conservation tillage [15]. These converging findings across independent Indo-Gangetic experiments establish residue-retained reduced tillage as a robust SOC-enhancing practice, operating through decreased macroaggregate turnover, increased physical protection of particulate organic matter, and reduced soil-to-residue contact that would otherwise accelerate decomposition [16].

3.2. Berseem Relay Cropping and Soil Organic Carbon

Direct evidence on berseem-integrated conservation agriculture, though more limited in volume than the cereal-focused literature, is methodologically strong and highly consistent. A five-year on-farm study evaluating the relay cropping of berseem in pearl millet–mustard (PM–M) systems under traditional tillage (TT), reduced tillage (RT), and zero tillage (ZT) found that relaying berseem (RB) residues provided surface cover under ZT that functioned as an organic carbon “sponge” supporting microbial activity, with soil quality improving progressively from TT to RT to ZT [11,17]. The retention of berseem legume residues, combined with the crop's biological nitrogen fixation, exerted a favorable compounding effect on soil physicochemical and biological properties, directly linking the CA tillage gradient to measurable soil-quality improvement in a system where berseem itself was the principal residue and carbon source [11]. A separate but closely related on-farm study (2017–18 to 2021–22) evaluating berseem relay-seeded into standing mustard across four preceding-crop scenarios, fallow, pearl millet, paddy, and green gram, found that including berseem as a relay crop in mustard cultivation significantly increased soil organic carbon and its stock, along with macro- and micronutrient availability and land-use efficiency, relative to existing non-legume cropping systems [12,18]. This study is particularly valuable because it isolates the specific contribution of berseem relay integration (rather than tillage alone) to SOC enhancement, demonstrating that the legume-residue and biological-nitrogen-fixation pathway operates as an independent, additive driver of SOC alongside any tillage-related mechanism [12].

Table 3: Summary of Selected Studies on Conservation Agriculture, Soil Carbon, and Berseem

Author(s) & Year	Location	System / CA Practice	Key SOC/Yield Outcome
Sharma *et al*., 2021 [11]	Semi-arid India	Berseem relay in pearl millet–mustard, TT/RT/ZT	Soil quality TT<RT<ZT; berseem residue acted as C sponge under ZT
Rana *et al*., 2025 [12]	Arid/semi-arid India	Berseem relay in mustard (4 preceding crops)	SOC and stock, micronutrients, land-use efficiency significantly increased
Bhattacharyya *et al*., 2023 [13]	Indo-Gangetic Plains	18-yr CA, ZT/CT/ST × residue mgmt	Macro-aggregate SOC +67.1% under residue-retained CT/ZT
Kumar *et al*., 2019 [14]	Rice-based system, India	6-yr ZT crop establishment × residue	TOC higher under ZT; very-labile C +21%, labile C +16%
Zhang *et al*., 2016 [15]	Rice–wheat rotation, China	Double conservation tillage (ZT + straw)	Macro-aggregates +17–29%; aggregate SOC 33.64 g kg^{-1}
Page *et al*., 2020 [16]	Global synthesis	Review: CA and SOC across systems	NT reduces aggregate turnover; physically protects SOC
Mishra *et al*., 2024 [19]	Eastern Oregon, USA	Legume (pea) rotation × tillage, dryland	Legume rotation enhanced long-term SOC storage
Almeida *et al*., 2024 [20]	Southern Brazil	Cover crop (vetch/radish/oat) × NT	NT carbon stock 80.22 Mg ha^{-1} vs. 61.09 Mg ha^{-1} under CT

3.3. Tillage System Interaction with Berseem and Companion-Crop Yield

Beyond SOC, the reviewed berseem-CA studies report substantial and consistent system-productivity benefits. In the five-year pearl millet–mustard relay-berseem study, the shift from traditional tillage to zero tillage, combined with berseem relaying, translated into measurable yield gains across the cropping system, attributed to the combined effects of improved soil physicochemical and biological properties and the residual nitrogen benefit of the legume phase [11]. In the companion mustard relay-cropping study, the enhancement of soil physicochemical properties through berseem integration led to increases in seed yield of pearl millet, paddy, and green gram by 10–15%, and mustard yield by 9–14%, compared with the existing (non-legume-relayed) cropping systems [12]. Mustard-equivalent yield (MEY) in the legume-based relayed-berseem systems increased by 33–66% relative to traditional cropping, generating additional net profit of approximately ₹40,000–51,000 ha^{-1}, and water productivity improved by 5–14% under most relay configurations, though it declined by 15% specifically when berseem was relayed following mustard grown after a fallow kharif season, indicating that the benefit is contingent on the preceding cropping sequence [12].

Notably, the highest berseem seed yield itself was recorded when berseem was relay-seeded in a fallow–mustard system, followed by green gram–mustard and pearl millet–mustard sequences, with the lowest berseem yield observed in paddy–mustard systems, suggesting that residual soil moisture and nutrient status from the preceding kharif crop materially influence berseem's own productivity within the relay-CA framework, independent of the tillage system applied [12]. This finding adds an important qualification to the otherwise consistent positive CA-berseem narrative: the choice of preceding crop in the rotation interacts with, and can partially offset or enhance, the benefits attributable to tillage and residue management alone.

3.4. Mechanistic Basis and Aggregate-Fraction Evidence

The mechanistic literature, drawn substantially from cereal-system CA research but directly applicable to interpreting berseem-CA findings, indicates that reduced tillage enhances SOC primarily through decreased physical disruption of soil macroaggregates, which in turn protects particulate organic matter from microbial decomposition and reduces direct soil-to-residue contact that would otherwise accelerate carbon turnover [16]. A long-term rice–wheat study found that conservation tillage combined with organic and chemical fertilizers increased macro-aggregates and micro-aggregates by 24.52%, 28.48%, and 18.12% (across size classes) relative to conventional tillage without residue return, with topsoil aggregate-associated carbon increasing markedly when zero tillage was paired with straw return and balanced fertilization [21]. These aggregate-stabilization mechanisms plausibly underlie the carbon “sponge” function attributed to retained berseem residues under zero tillage in the PM–M relay study, in which surface-retained legume biomass would be expected to similarly reduce soil disturbance and protect newly added organic carbon from rapid mineralization [11]. Legume-specific mechanistic evidence further reinforces this picture: a long-term Oregon dryland-wheat study found that incorporating legume (spring pea) rotations enhanced long-term soil carbon storage relative to continuous wheat–fallow under both conventional and no-till management, attributing the effect to eliminated fallow periods, reduced tillage intensity, and rotational diversification, three principles directly analogous to the berseem-relay mechanism of eliminating an otherwise fallow or low-residue period in the cropping calendar [19]. A Brazilian cover-crop and no-tillage study similarly found that no-till plots achieved the highest carbon stock (80.22 ± 0.77 Mg ha^{-1}) regardless of cover-crop species, with the lowest stock (61.09 ± 0.69 Mg ha^{-1}) recorded under conventional tillage with a legume cover crop (common vetch), indicating that tillage reduction, rather than legume presence alone, was the dominant driver of carbon accrual in that system, an important nuance for interpreting the relative contributions of CA's tillage and crop-diversification pillars [20].

3.5. Contradictory Findings and Contextual Moderators

Despite the generally consistent CA-SOC-positive findings reviewed above, the broader literature documents notable exceptions in which tillage has been observed to increase, rather than decrease, SOC relative to no-till systems. A review on CA's ability to conserve SOC explicitly cites multiple instances in which tillage increased SOC stores relative to CA systems, attributing this contextual reversal to factors such as soil type, climate, depth of sampling, and the specific tillage and residue-management combination tested [16]. In areas where full-inversion tillage buries residues in poorly aerated subsurface zones, decomposition can be slowed relative to surface placement, particularly under cool, moist conditions, complicating any universal claim that tillage reduction inevitably increases SOC across all contexts and depths [16]. This contradiction underscores that the magnitude and even direction of CA's SOC effect is moderated by local pedoclimatic conditions and sampling depth, a caveat that the relatively young berseem-specific literature has not yet systematically tested across diverse agro-ecologies.

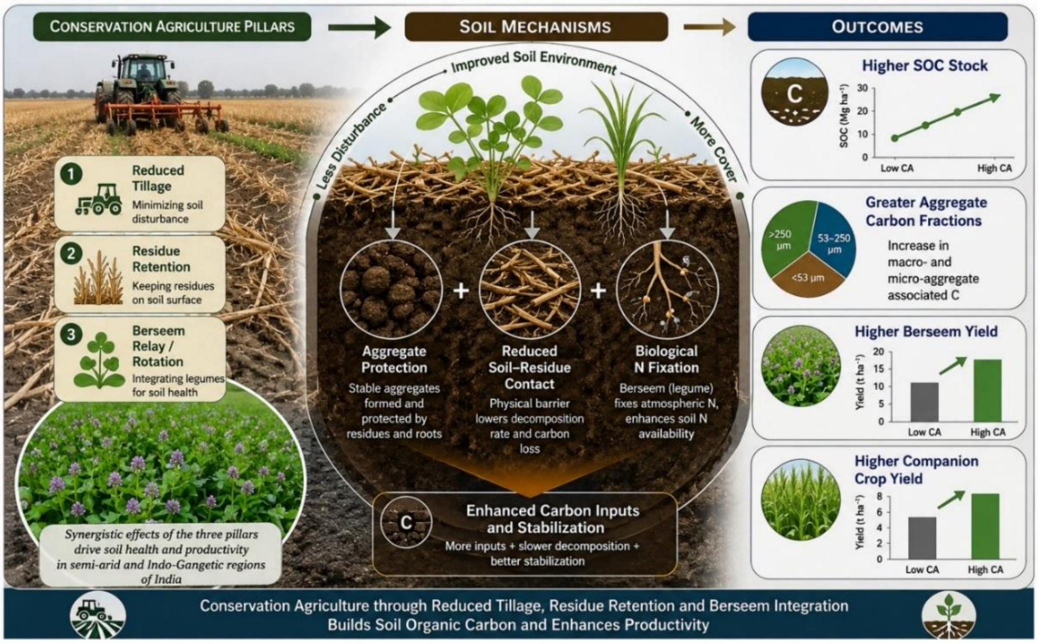

Fig 3: Conceptual framework linking conservation agriculture pillars (reduced tillage, residue retention, berseem relay/rotation) to soil mechanisms (aggregate protection, reduced soil-residue contact, biological N fixation) and final outcomes (SOC stock, aggregate carbon fractions, berseem and companion-crop yield).

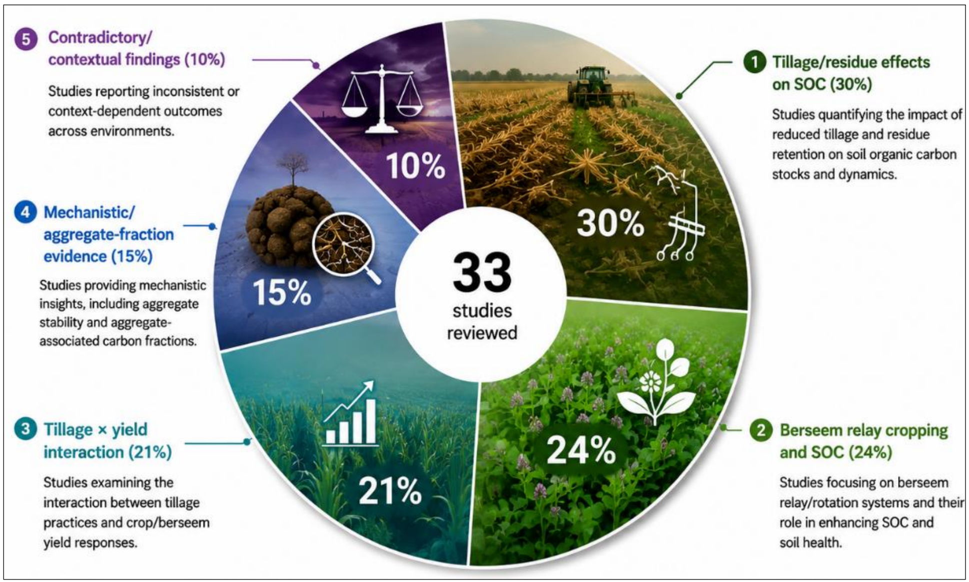

Fig 4: Thematic classification of the 33 reviewed studies by primary focus: tillage/residue effects on SOC (30%), berseem relay cropping and SOC (24%), tillage × yield interaction (21%), mechanistic/aggregate-fraction evidence (15%), and contradictory/contextual findings (10%).

4. Comparative Analysis of Previous Studies

Table 4 presents a structured comparison of methodologically diverse studies, highlighting differences in location, design, and reported limitations that constrain direct cross-study comparison.

Table 4: Comparative Analysis of Previous Research on Conservation Agriculture, Soil Carbon, and Berseem

Author/Year	Location	Methodology	Major Findings	Limitations
Sharma *et al.*, 2021 [11]	Semi-arid India	5-yr on-farm, TT/RT/ZT × berseem relay in PM–M	ZT + relay berseem best soil quality and system yield	Single agro-ecology; on-farm variability across years
Rana *et al.*, 2025 [12]	Arid/semi-arid India	5-yr on-farm, berseem relay × 4 preceding crops	SOC, micronutrients, MEY (+33–66%) significantly increased	On-farm design; preceding-crop confounding with tillage
Bhattacharyya *et al.*, 2023 [13]	IGP, India	18-yr CA trial, 3 tillage × 3 residue levels	Macro-aggregate SOC +67.1% under residue-retained tillage	Cereal (rice–wheat) system; not berseem-specific
Kumar *et al.*, 2019 [14]	India (rice-based)	6-yr split-plot, 4 establishment × 2 residue × 2 systems	TOC and labile C fractions higher under ZT	Six years may be insufficient for passive-C equilibrium
Zhang *et al.*, 2016 [15]	China (rice–wheat)	Field trial, double CT vs. CA tillage × straw	Aggregate stability and SOC markedly higher under CA	Single rotation system; China-specific soil type
Mishra *et al.*, 2024 [19]	Oregon, USA	Long-term, legume rotation × tillage, dryland	Legume rotation enhanced long-term SOC vs. fallow	Temperate dryland; not directly transferable to subtropics
Almeida *et al.*, 2024 [20]	S. Brazil	4.5-yr, 3 tillage × 3 cover crops	NT dominant driver of C stock over cover-crop species	Medium-term (4.5-yr); single soil type

A clear pattern across Table 4 is that the two studies most directly relevant to berseem (Sharma *et al.* and Rana *et al.*) are robust, multi-year, on-farm investigations but remain geographically confined to semi-arid and arid India, while the broader mechanistic and aggregate-fraction evidence supporting the plausibility of their findings derives predominantly from cereal-based systems in other regions (China, the Indo-Gangetic Plains, the USA, and Brazil). This pattern, strong direct evidence in a narrow geographic and cropping-system range, supported by strong indirect mechanistic evidence from a wider range of systems, defines both the strength and the principal limitation of the current berseem-CA evidence base.

5. Research Gaps and Emerging Trends

5.1. Unresolved Issues and Knowledge Gaps

Several gaps persist. First, berseem-specific CA-SOC research remains geographically concentrated in semi-arid and arid Indian cropping systems (pearl millet–mustard, mustard relay), and multi-location validation across other berseem-growing regions, including the Nile Valley, Pakistan, and the broader Mediterranean, is largely absent [11,12]. Second, the relative contribution of berseem's root-versus-shoot biomass to SOC accrual has not been disaggregated in the reviewed berseem-specific studies, despite root-derived carbon being recognized in the broader CA-SOC literature as often more persistent than aboveground residue carbon [13,16]. Third, the interaction between CA tillage system and berseem cutting management (number and timing of fodder cuts, which directly determine the quantity of residual root and stubble biomass returned to soil) remains unexamined, representing a berseem-specific agronomic variable with no cereal-system analogue [2,11]. Fourth, the documented instances in the broader literature where tillage increased rather than decreased SOC have not been tested for berseem-integrated systems specifically, leaving open the possibility that the strongly positive berseem-CA findings to date may not generalize to all soil types and climates [16]. Fifth, quantitative

SOC sequestration rates (Mg C ha^{-1} yr^{-1}) specific to berseem-CA systems, as opposed to qualitative "significant increase" findings, are rarely reported, limiting integration into carbon-credit or climate-mitigation accounting frameworks [11,12].

Table 5: Research Gaps Identified in the Reviewed Literature

Gap Category	Description	Implication
Geographic concentration	Berseem-CA evidence concentrated in semi-arid/arid India	Limited generalizability to Nile Valley, Pakistan, Mediterranean systems
Root vs. shoot carbon contribution	Berseem-specific studies do not disaggregate root/shoot SOC input	Mechanistic understanding of carbon source incomplete
Cutting management interaction	CA × berseem fodder-cutting frequency/timing unexamined	Management lever specific to forage legumes left unoptimized
Contextual SOC reversals untested	Tillage-increases-SOC cases not evaluated for berseem systems	Uncertainty whether positive findings generalize across soils/climates
Quantitative sequestration rates	Mg C ha^{-1} yr^{-1} rarely reported for berseem-CA systems	Limits integration into carbon-credit/climate-mitigation frameworks
Long-term, multi-decadal trials	Most direct berseem-CA evidence spans 5 years	Passive-carbon-pool equilibrium and stability not yet captured

5.2. Emerging Technologies and Future Developments

Emerging directions include the application of soil-carbon fractionation techniques (particulate, mineral-associated, and aggregate-occluded carbon pools) to berseem-CA systems, building on the methodological approaches already validated in cereal-based CA research, to disaggregate labile and passive carbon responses specific to legume residue input [14]. Long-term experimental network approaches, analogous to the 18-year Indo-Gangetic CA trial, represent a second priority, extending berseem-relay systems into multi-decadal monitoring to capture passive-carbon-pool equilibration that shorter trials cannot detect [13]. Remote-sensing and isotopic (δ13C) tracing methods, increasingly used to partition root-versus-shoot carbon contributions in legume-cereal rotations elsewhere, offer a promising avenue for resolving the root-carbon knowledge gap specific to berseem [19]. Finally, integration of berseem-CA findings into formal carbon-credit and climate-mitigation accounting frameworks, contingent on the quantitative sequestration-rate data identified as a gap above, would translate the qualitative SOC benefits already documented into actionable policy and market mechanisms [16].

Table 6: Emerging Trends in Conservation-Agriculture Research Relevant to Berseem

Emerging Trend	Description	Potential Benefit
Carbon-pool fractionation methods	Disaggregating labile, occluded, and passive SOC fractions	Mechanistic clarity on berseem-specific carbon stabilization
Long-term multi-decadal CA trials	Extending berseem-relay monitoring beyond 5–10 years	Captures passive-carbon equilibrium and system stability
Isotopic (δ13C) root-tracing	Partitioning root- vs. shoot-derived SOC contribution	Resolves root-carbon knowledge gap specific to legumes
Carbon-credit/climate-accounting integration	Quantitative Mg C ha^{-1} yr^{-1} reporting for berseem-CA systems	Enables policy and market-based incentive mechanisms
Cutting-management × CA optimization	Systematic testing of fodder-cut frequency under CA tillage	Identifies management combination maximizing fodder and SOC jointly

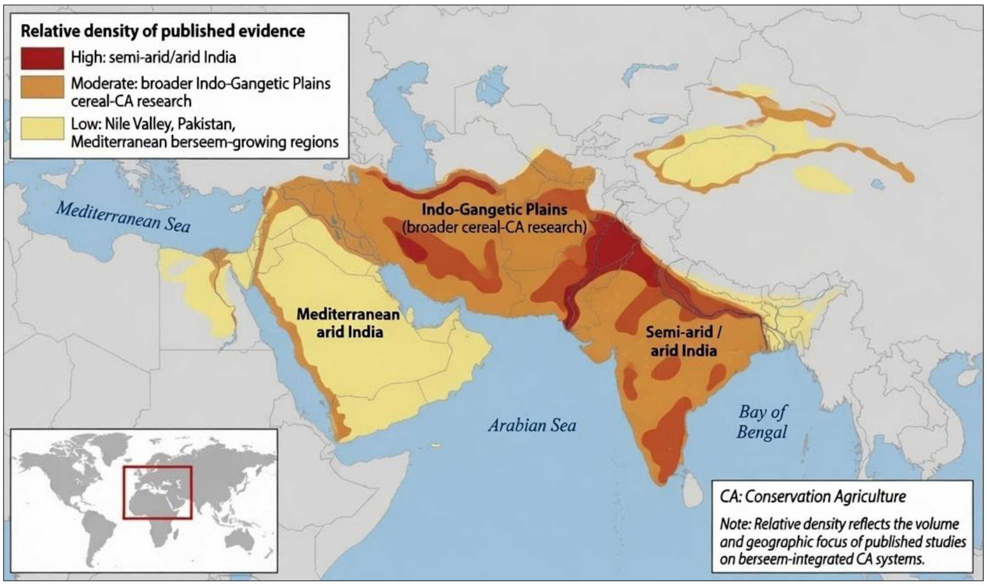

Fig 5: Research gap mapping showing relative density of published evidence across geographic regions (high: semi-arid/arid India; moderate: broader Indo-Gangetic Plains cereal-CA research; low: Nile Valley, Pakistan, Mediterranean berseem-growing regions) for berseem-integrated conservation agriculture.

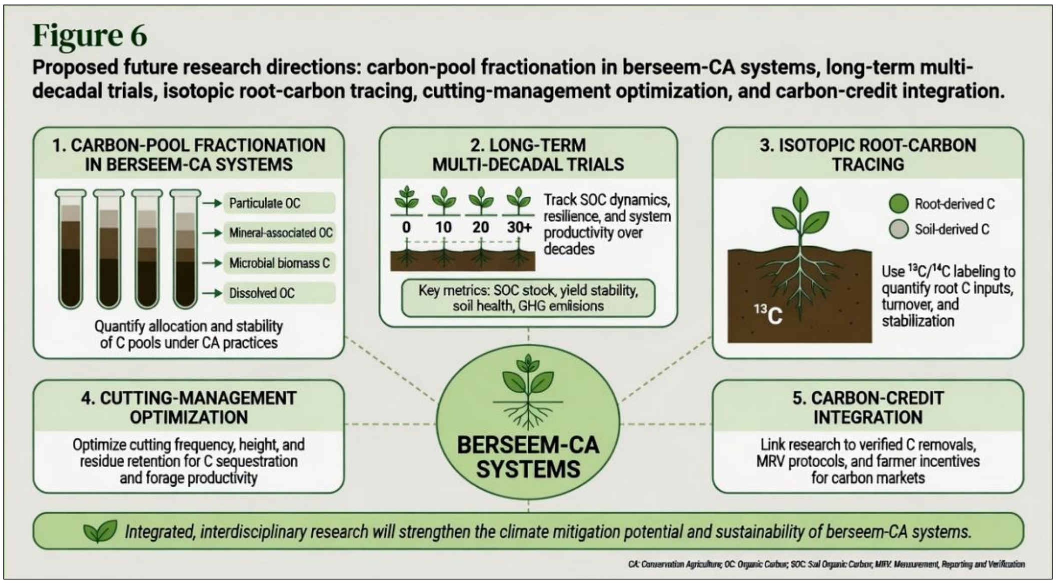

Fig 6: Proposed future research directions: carbon-pool fractionation in berseem-CA systems, long-term multi-decadal trials, isotopic root-carbon tracing, cutting-management optimization, and carbon-credit integration.

6. Discussion

The synthesized evidence supports the conclusion that conservation agriculture, particularly when integrated with berseem as a relay or rotational legume, enhances both soil organic carbon and system productivity relative to conventional tilled, non-legume cropping. The two berseem-specific studies reviewed here are notably convergent: both report significant SOC increases alongside substantial yield and productivity gains across the cropping system, with the zero-tillage, relay-berseem combination consistently identified as the most favorable configuration [11,12]. This convergence, achieved through independent on-farm trials conducted over multiple years in related but distinct cropping systems (pearl millet–mustard and multi-crop–mustard relay), lends meaningful credibility to the core finding despite the relatively narrow geographic scope of the direct evidence base.

A central interpretive theme is the apparent additivity of CA's tillage and crop-diversification pillars when berseem is the integrated legume. The tillage-gradient evidence (TT<RT<ZT in soil quality) and the legume-residue evidence (SOC and stock increased through berseem relay specifically) appear to operate through complementary, not redundant, mechanisms: reduced tillage protects existing and newly added organic matter from rapid turnover, while berseem residue and biological nitrogen fixation supply the additional carbon and nitrogen inputs that protected aggregates then stabilize [11,16]. This mechanistic complementarity is consistent with, and reinforced by, the broader cereal-system CA literature demonstrating that residue-retained reduced tillage increases macro-aggregate carbon and labile carbon fractions through reduced soil disturbance [13,14,15].

A point requiring careful interpretation is the Brazilian cover-crop finding that no-tillage, rather than the presence of a legume cover crop, was the dominant driver of carbon-stock differences, with the lowest carbon stock recorded under conventional tillage despite a legume (vetch) cover crop being present [20]. This suggests that tillage reduction may be a necessary, and in some contexts more influential, condition than legume presence alone for realizing SOC gains, a nuance with direct relevance to interpreting the berseem-CA literature: the strong positive findings in the Indian relay-berseem studies may be partially attributable to the accompanying tillage reduction (TT to ZT) rather than to the berseem legume phase in isolation, an attribution the existing studies do not fully disentangle [11,20].

A further point of caution concerns the documented contextual reversals in which tillage increased rather than decreased SOC in some cereal systems, attributed to soil type, climate, and sampling depth [16]. Because the direct berseem-CA evidence to date derives exclusively from semi-arid and arid Indian conditions, it remains untested whether the same positive CA-SOC relationship would hold under different pedoclimatic conditions, for example in the cooler, moister soils where inversion tillage has sometimes been found to favor SOC retention through different residue-placement dynamics. This represents the most significant unresolved question for generalizing current berseem-CA recommendations beyond their tested geographic range.

From a practical standpoint, the evidence strongly supports promoting berseem relay or rotational integration within zero- or reduced-tillage systems as a productivity- and soil-carbon-positive strategy, particularly in semi-arid cereal- and oilseed-dominated systems resembling those tested. The substantial reported gains, mustard-equivalent yield increases of 33–66%, companion-crop yield gains of 9–15%, and significant SOC enhancement, represent an unusually favorable combination of agronomic and environmental outcomes rarely achieved simultaneously in single-intervention agronomic research, underscoring the practical importance of this integrated CA-legume strategy [12].

7. Conclusion

In this research study, thirty-three published peer-reviewed papers were scrutinized from the years 2015 to 2025 in order to analyze the correlation between conservation agriculture, soil organic carbon, and crop yield of berseem (*Trifolium alexandrinum*). The findings indicate that conservation agriculture that is performed with zero tilling or reduced tilling with the integration of berseem relay or rotation has increased the levels of soil organic carbon as well as the soil carbon. Furthermore, conservation agriculture has led to an increase in the productivity of agricultural production (the crop yield of berseem has increased by 9-15% and the mustard equivalent yield has increased by 33-66%, while water productivity has increased by 5-14% as presented in the direct studies conducted in the berseem field). The above findings align with other research papers concerning CA as an important component of cereal crop systems, in which the role of conservation agriculture is considered important in retaining residues and minimizing the loss of soil organic carbon through the formation of stable aggregates as well as low contact ratio of the soil and residues.

This study therefore suggests that more research should be conducted in different regions that have different environmental conditions regarding newly designed berseem systems excluding semi-arid regions of India as well as on the issues like separate carbon contribution of leaves and roots together with berseem cutting combined with conservation tillage.

This study's results would motivate policy makers and practitioners to propagate such systems as berseem relay or rotation integration in zero or reduced tillage cropping systems based on soil carbon increase and productivity improvement approach just as the case with semi-arid pearl millet–mustard and alike systems. Nevertheless, one should be cautious in the context of extending the results to absolutely different pedo-climatic conditions until proven differently.

In the future, new research should therefore concentrate on the extension of applicability of berseem-CA findings to other areas of the world with the help of isotopic and fractionative methods of analysis as well as elaboration of quantitative carbon accounting indicators that would help in successful implementation of policies focused on the benefits of conservation agriculture concerning berseem use.

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