



Conservation Agriculture in Indian Agroecosystems: A Systematic Review and Meta-Analysis of Crop Productivity, Soil Carbon and Water-Use Efficiency

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Abstract

Conservation agriculture (CA), founded on minimum soil disturbance, permanent soil cover and crop diversification, is promoted as a pathway to improve agricultural productivity while conserving soil carbon and water. This article synthesizes quantitative meta-analytic evidence and selected long-term field studies relevant to Indian agroecosystems. A South Asian meta-analysis based on 9,686 paired site-year comparisons reported that zero tillage combined with residue retention was associated with a mean 5.8% yield advantage and a 12.6% increase in water-use efficiency, while a country-focused meta-analysis of 544 paired observations from 35 Indian publications reported a 1.15% average yield reduction under CA compared with conventional tillage, alongside increases of 8.9% in soil organic carbon (SOC) content and 7.3% in soil carbon sequestration (Jat *et al.*, 2020; Padbhushan *et al.*, 2024) ^[5, 10]. These results are not necessarily contradictory: they differ in geography, eligible studies, treatment definitions, cropping systems and moderators. Long-term evidence from the middle Indo-Gangetic Plains also shows that diversified systems combining reduced tillage and legumes can improve rice-equivalent productivity and water productivity, although results are treatment-specific (Rao *et al.*, 2022) ^[12]. Across Indian studies, CA's most defensible benefits are improved soil cover and structure, enhanced SOC indicators under sustained residue inputs, and greater water productivity in well-matched systems. Yield effects remain contingent on crop, soil texture, rainfall, nutrient supply, weed management, duration and machinery access. This is a structured review of published quantitative syntheses, not a newly recalculated study-level meta-analysis: a *de novo* pooled estimate was not produced because harmonized raw data and a complete database screening log were not assembled for this draft. The review therefore reports published estimates separately and outlines the protocol needed for a fully reproducible submission.

Keywords: Conservation agriculture, crop productivity, soil organic carbon, water-use efficiency, zero tillage, crop residues, India, meta-analysis

Introduction

Indian agriculture spans irrigated alluvial plains, rainfed semi-arid zones, black-soil plateaus, coastal systems and hill agroecosystems. Across these settings, farmers face linked pressures: rising production costs, declining soil structure in intensively tilled fields, residue burning or removal, uneven rainfall, groundwater stress and yield variability. Conservation agriculture (CA) seeks to address several of these challenges by managing the soil as a living system rather than treating tillage as the default means of seedbed preparation. The Food and Agriculture Organization (FAO, n.d.) describes three linked principles: continuous minimum mechanical soil disturbance, permanent organic soil cover, and crop-species diversification through rotations or associations. CA is not synonymous with zero tillage alone. No-till can be introduced without retaining residues or diversifying crop sequences; such partial adoption may deliver some operational benefits but not the full ecological functions intended by CA. Soil cover intercepts rainfall, reduces direct soil evaporation and moderates surface temperature; minimal disturbance can protect aggregates and soil biota; and crop diversification can distribute rooting depths and nutrient demand across seasons. These mechanisms create plausible pathways for greater water-use efficiency and soil carbon retention, but their strength

depends on residue supply, climate, soil texture, crop choice and management quality (FAO, n.d.; Sawant *et al.*, 2026) ^[13].

The quantitative literature illustrates why context matters. Jat *et al.* (2020) ^[5] synthesized 9,686 paired site-year comparisons in South Asia and reported gains for several CA component practices, including zero tillage with residue retention. By contrast, the Indian meta-analysis by Padbhushan *et al.* (2024) ^[10] found a small but statistically significant average yield reduction across its included observations, even while reporting positive effects on SOC and carbon sequestration. A global meta-analysis of no-till-only comparisons similarly estimated a mean yield reduction, with stronger performance in dry rainfed settings and after the transition period (Pittelkow *et al.*, 2015) ^[11]. These analyses answer related but non-identical questions: CA bundles several practices, whereas no-till isolates tillage, and a regional synthesis may include a different mix of cropping systems than a national one.

This review therefore examines three outcomes that are central to the Indian policy and farm-management debate: (i) crop productivity and its stability, (ii) soil organic carbon and related soil-quality indicators, and (iii) water-use efficiency or water productivity. It also considers heterogeneity, farm-level constraints and the limitations of current evidence, with emphasis on the distinction between

results established in Indo-Gangetic cereal systems and the more limited quantitative evidence for diverse rainfed systems across central and peninsular India.

Conceptual framework

1. Defining conservation agriculture

For this review, CA means a system that combines minimum soil disturbance, sustained soil cover and crop diversification, adapted to local production conditions. The FAO identifies at least 30% soil cover after seeding as a practical threshold for classifying a field as under CA and describes diversification through sequences or associations involving multiple crop species (FAO, n.d.). In research, however, treatment labels vary: some experiments test zero tillage alone, others combine zero tillage with residue retention, and others add raised beds, legumes, direct-seeded rice, cover crops or precision nutrient management. These treatments should not be treated as interchangeable.

2. Outcomes and measurement choices

Crop productivity can be reported as yield of an individual crop, rice-equivalent yield, total system productivity, gross margin or yield stability. The first three measure production, while gross margin includes costs and yield stability captures interannual risk. SOC should ideally be assessed as a stock (mass of carbon per unit area to a specified depth), alongside concentration, bulk density and equivalent soil mass; a change in concentration alone is not necessarily a change in the total carbon stock. Water-use efficiency is also non-uniform: it may mean grain produced per unit of irrigation water applied, per unit of evapotranspiration, or per unit of total water input. This article retains the original metrics reported by each study and avoids combining non-equivalent measures.

Materials and methods

1. Review questions

The review was organized around four questions:

1. Under which conditions does CA improve or reduce crop and cropping-system productivity?
2. What evidence supports changes in SOC and carbon sequestration?
3. How do CA practices influence water-use efficiency or water productivity?
4. Which environmental, technical and institutional factors explain differences between Indian agroecosystems?

2. Evidence identification and eligibility

A structured search of publicly indexed journal pages, abstract records, institutional repositories and methodological guidance was undertaken on 22 October 2026. Search strings combined terms such as “conservation agriculture”, “zero tillage”, “residue retention”, “crop productivity”, “soil organic carbon”, “water-use efficiency”, “water productivity”, “India”, “Indo-Gangetic Plains”, “meta-analysis” and “long-term experiment”. Key records were followed through their reference lists where available. Priority was given to peer-reviewed meta-analyses, Indian field experiments with a defined comparison treatment, and long-term studies reporting one or more of the target outcomes. FAO material was used for operational definitions and Page *et al.* (2021) ^[9] for review-reporting guidance.

Eligible evidence included studies comparing CA practices or clearly described components with conventional tillage or prevailing farmer practice in India, together with South Asian or global meta-analyses useful for interpreting Indian findings. Studies were considered relevant if they reported crop yield or system productivity, SOC or soil carbon sequestration, or water-use efficiency/water productivity. Editorials without identifiable methods and studies that discussed sustainability without a measured comparison were not used to derive quantitative results. The evidence base is purposive and structured; it should not be interpreted as a completed Scopus/Web of Science systematic search because record-level exports and a full duplicate-screening log were not assembled for this manuscript draft.

3. Data extraction and synthesis

For each core source, the synthesis recorded study geography, evidence type, number of comparisons where reported, practices contrasted, outcomes and principal quantitative findings. Published meta-analytic results were retained in their original form. They were not arithmetically averaged across studies because the underlying evidence sets may overlap, outcome definitions differ, and the standard errors needed for a valid second-stage model were not available in a consistently harmonized form. Field-study values are presented as case evidence, not as national pooled effects.

4. Meta-analysis status and protocol for a de novo analysis

A new study-level meta-analysis was not calculated for this draft. Doing so would require extracting treatment and control means, sample sizes and measures of dispersion from every eligible experiment, checking repeated observations and shared controls, and standardizing outcomes. A reproducible follow-up analysis should preregister eligibility criteria; search Scopus, Web of Science, CAB Abstracts, AGRICOLA and relevant Indian journal repositories; screen records in duplicate; and publish a PRISMA 2020 flow diagram (Page *et al.*, 2021) ^[9]. For continuous outcomes, a log response ratio, $\ln(\text{meanCA} / \text{meanCT})$, could be used when means are positive and comparable, with sampling variances calculated from study-level sample sizes and standard deviations. Random-effects models, preferably with robust uncertainty estimation when dependence remains, should be accompanied by subgroup analyses for crop, agroecological zone, soil texture, residue retention, nutrient management and years since adoption. SOC should be stratified by depth and reported as concentration and stock; water outcomes should be split by irrigation input and evapotranspiration definitions.

Results

1. Quantitative evidence at a glance

The strongest quantitative messages are directionally consistent for soil carbon and water productivity, but mixed for yield. The South Asian synthesis reports that particular CA combinations deliver appreciable average benefits, while the India-focused synthesis reports a small average yield penalty across its broader set of comparisons. Field experiments reinforce the importance of rotations, residue management, transition duration and system-level assessment. The estimates in Table 1 must be read within each source’s specific scope.

Table 1: Principal quantitative findings from published syntheses and select4ed Indian field evidence

Source and scope	Evidence base / practice	Productivity finding	Soil carbon or water finding
Jat <i>et al.</i> (2020) ^[5] , South Asia meta-analysis	9,686 paired site-year comparisons; multiple CA components	Zero tillage + residue retention: mean yield advantage of 5.8%	Water-use efficiency +12.6%; net economic return +25.9%; global warming potential reduced by 12–33% for the reported practice comparison
Padbhushan <i>et al.</i> (2024) ^[10] , India meta-analysis	544 paired CA–conventional observations from 35 publications	Overall yield 1.15% lower under CA; responses varied by region, crop and soil texture	SOC content +8.9%; soil carbon sequestration +7.3% versus conventional tillage
Pittelkow <i>et al.</i> (2015) ^[11] , global no-till meta-analysis	6,005 paired observations from 678 studies; no-till compared with conventional tillage	Mean yield –5.1%; rainfed dry climates performed best; yield response varied by crop and duration	Not a pooled SOC or WUE estimate; highlights management and climate moderation
Rao <i>et al.</i> (2022) ^[12] , Patna, India	Seven-year field experiment; CA/BMP and diversified rotations	Some systems raised annual rice-equivalent yield by 30.5–34.4% relative to the residue-removed rice–wheat–fallow control	Water productivity was 1.04 kg rice-equivalent grain m ^{–3} in the best-performing system versus 0.64 kg m ^{–3} in the control
Kumar <i>et al.</i> (2022) ^[6] , north-west India	Three-year rice–wheat experiment with different establishment and residue treatments	Rice yield response was treatment- and variety-dependent; conventional transplanted rice had an advantage for rice in this experiment	SOC reached 7.5 g kg ^{–1} in the 0–15 cm layer under a direct-seeded rice/zero-till wheat full-residue treatment; one CA-based treatment reduced system GWP by 43% versus farmer practice
Mahala <i>et al.</i> (2023) ^[7] , eastern Indo-Gangetic Plains	SOC analysis following a long-term trial initiated in 2006	Not designed as a pooled yield estimate	Zero tillage with residue retention increased very labile, labile, less-labile and non-labile SOC fractions; carbon management index was highest under the combined practice

Note. Percentages and units are reproduced from the cited publications and are not new pooled estimates calculated in this article. The studies differ in geographical scope and intervention definition; their estimates must not be added or averaged. GWP = global warming potential; SOC = soil organic carbon; BMP = best-management practice; WUE = water-use efficiency.

2. Crop productivity: management bundles outperform simplistic prescriptions

The yield response to CA is heterogeneous rather than universally positive. Jat *et al.* (2020) ^[5] reported a mean yield advantage for zero tillage combined with residue retention in South Asia, with more favourable results on loamy soils and in maize–wheat systems. The Indian meta-analysis, however, reported a modest average yield reduction of 1.15%, with increases in western, northern and north-western regions but decreases in eastern, north-eastern and southern regions in the datasets it analyzed (Padbhushan *et al.*, 2024) ^[10]. These results caution against using a single national average to predict a farmer's outcome.

A central reason is that CA is a management system, not a single input. The global meta-analysis by Pittelkow *et al.* (2015) ^[11] found that no-till yields were lower on average when compared with conventional tillage in isolation, but the penalty was smaller after several years and under dry rainfed conditions. It also showed crop-specific differences and identified nitrogen supply and residue management as important moderators. This finding helps reconcile mixed studies: if no-till is introduced without suitable nutrient placement, weed management or residue cover, early yield reductions may occur; if combined with timely seeding, suitable varieties, good nutrient management, residue retention and rotation, the system can become more productive and cost-efficient over time.

Long-term Indian evidence supports assessing the whole rotation rather than one crop in isolation. Rao *et al.* (2022) ^[12] reported that avoiding tillage in wheat and including a food legume in a diversified rotation increased annual rice-equivalent yield by 30.5–34.4% in selected systems at Patna. The same experiment found that a diversified potato–maize–cowpea–rice system delivered the highest reported water productivity. These outcomes should not be attributed to zero tillage alone: rotation, crop intensification, residue handling and other best-management practices were bundled

in the treatment. The practical lesson is that system design and complementary agronomy determine whether resource savings translate into productivity gains.

The north-west India experiment reported by Kumar *et al.* (2022) ^[6] also illustrates why CA cannot be assessed only through crop yield in a single season. Rice yield favoured conventional transplanted rice in that particular trial, while a zero-tillage/direct-seeded rice and zero-tillage wheat combination with residues improved selected soil indicators and reduced greenhouse-gas impacts versus farmer practice. A technology can therefore offer environmental or resource benefits even when its yield response is neutral or negative in one crop-year. Whether that trade-off is acceptable depends on net returns, water savings, system yield and the time horizon of evaluation.

3. Soil organic carbon and soil-function indicators

The quantitative evidence for positive carbon indicators is comparatively consistent. Padbhushan *et al.* (2024) ^[10] reported mean increases of 8.9% in SOC content and 7.3% in soil carbon sequestration under CA compared with conventional tillage across their Indian evidence base. In a long-term eastern Indo-Gangetic rice–wheat experiment, Mahala *et al.* (2023) ^[7] found that zero tillage combined with residue retention increased all four examined SOC fractions (very labile, labile, less labile and non-labile) and produced the highest carbon-management-index values among treatments. Dey *et al.* (2020) likewise examined organic and inorganic carbon sequestration and carbon lability in a calcareous rice–wheat soil, demonstrating the importance of soil type and carbon fractions when interpreting CA effects.

The probable mechanisms are increased carbon inputs from retained residues and roots, less aggregate disruption, improved aggregation and a shift in the distribution of carbon among soil fractions. Surface accumulation is often more pronounced than change at depth; therefore, sampling

depth and the method for calculating stock can change the apparent magnitude of an effect. A measured rise in SOC concentration in the topsoil should not automatically be translated into an equivalent increase in whole-profile sequestration. Future syntheses should report sampling depth, bulk density, coarse fragments and equivalent soil mass where possible, and distinguish stable stock change from short-term surface enrichment.

SOC gains also depend on the amount and quality of biomass returned to the field. Where residues are removed for fodder, fuel or household use, maintaining the soil-cover principle can be difficult. A strategy that assumes all residues can be retained may not be feasible for mixed crop–livestock farms. Locally adapted systems can consider partial residue retention, cover crops, legume integration, manure and tree-based biomass while documenting the quantity of carbon actually returned. This is especially important when transferring findings from mechanized rice–wheat systems to rainfed pulse, millet, soybean or cotton systems.

4. Water-use efficiency and water productivity

CA can alter the crop water balance through reduced direct evaporation, better protection against raindrop impact, changes in infiltration and runoff, improved soil aggregation and more timely field operations. Residue cover can reduce soil-surface temperature and evaporation, while rotations with different rooting profiles can improve seasonal capture of water. These mechanisms are consistent with the 12.6% WUE increase reported for zero tillage plus residue retention in the South Asian meta-analysis by Jat *et al.* (2020)^[5].

Indian field evidence also suggests that cropping-system design matters. At Patna, Rao *et al.* (2022)^[12] measured water productivity of 1.04 kg rice-equivalent grain m⁻³ in the best-performing diversified system, compared with 0.64 kg m⁻³ under a residue-removed rice–wheat–fallow control. The result is promising, but water productivity based on system output and water input is not automatically equivalent to crop water-use efficiency based on evapotranspiration. The studies should not be combined until units and denominators are harmonized.

The water benefit is not guaranteed. In heavy soils or poorly drained settings, residue cover and reduced disturbance can interact with waterlogging or delayed sowing. In rice, transplanting, puddling, direct seeding and irrigation schedules affect both water demand and weed pressure. Conservation agriculture should therefore be integrated with irrigation scheduling, drainage, crop choice and soil-specific nutrient management rather than treated as a substitute for water governance. An efficiency gain at field level also does not necessarily reduce basin-scale water consumption if farmers use the saved water to expand irrigated area or grow more water-demanding crops.

5. Regional coverage and transferability

Much of the strongest Indian quantitative evidence comes from cereal systems in the north-western and eastern Indo-Gangetic Plains. These regions have established research on zero-till wheat, direct-seeded rice, residue retention, permanent beds and rice–wheat or rice–maize rotations. Long-term trials and meta-analyses are useful for estimating effects in those systems, but they do not represent all Indian agroecosystems equally. Recent synthesis work identifies

substantial heterogeneity in crop response, SOC change, water dynamics and adoption according to climate, soils, residue availability, machinery and management (Sawant *et al.*, 2026)^[13].

Central and peninsular India include diverse rainfed systems, including soybean, sorghum, millets, pulses, cotton and mixed rotations on Vertisols and other soil groups. In these contexts, the aim may be to conserve episodic rainfall, reduce runoff and crusting, preserve soil moisture for flowering and grain filling, and improve resilience to dry spells. However, national mean estimates from the rice–wheat literature should not be transferred directly to these systems. Research is needed that compares full CA packages with locally relevant farmer practice across rainfall gradients and soil types, while recording residue competition, planting windows and the availability of suitable seeders.

Discussion

1. Why published yield estimates differ

Differences across meta-analyses arise from at least five sources. First, the unit of intervention differs: no-till alone is not equivalent to full CA or to a diversified, residue-retained system. Second, geography differs: global, South Asian and India-only syntheses include different climatic and soil distributions. Third, yield is reported as either individual crop yield or system-level equivalent yield. Fourth, the duration since implementation matters because transition effects and learning costs are concentrated in early years. Fifth, comparisons may vary in nutrient management, weeds, seeding equipment and crop variety. These factors explain why a modest negative national average can coexist with positive effects for particular combinations.

The prudent conclusion is not that the evidence is irreconcilable, but that the average treatment effect is incomplete without moderators. Extension messages should explain where the practice is most likely to work, what complementary management is required, and what early transition risks to plan for. A farmer deciding whether to adopt CA needs expected net margin and labour requirements as well as yield. Public programmes evaluating outcomes should monitor whole-system production and stability rather than reward adoption of a single component.

2. Soil carbon: ecological benefit and accounting discipline

CA can improve carbon inputs and protection, but carbon outcomes should be interpreted carefully. A higher SOC concentration close to the soil surface is a meaningful soil-health signal, yet it may partly reflect stratification after tillage is reduced. Long-term sequestration should be assessed through repeated, depth-consistent sampling and appropriate stock calculations. Carbon permanence also depends on continued residue inputs and future management; gains can be reversed if a system returns to intensive tillage or exports biomass. The article therefore treats SOC as an important indicator rather than assuming every reported topsoil change represents permanent additional carbon removal.

3. Water efficiency is not always water saving

More grain per unit of irrigation water is beneficial at the farm scale, but policy should distinguish productivity from

absolute water consumption. If saved water is used to increase cropped area or shift to water-demanding crops, total extraction may not fall. Future studies should measure irrigation applied, rainfall, evapotranspiration where feasible, runoff, drainage and system output. In rainfed regions, yield per unit of rainfall and soil-moisture dynamics may be more informative than irrigation water productivity. Basin-level effects require hydrological accounting beyond the plot.

4. Adoption constraints and equity

Farmers do not adopt practices solely on the basis of agronomic averages. Timely access to zero-till drills, residue-handling machinery, repair services, agronomic advice, credit and reliable markets all shape feasibility. Crop residues may be essential livestock feed, and farmers can face weed-control costs or uncertainty during transition. The 2026 Indian review by Sawant *et al.* (2026)^[13] identifies

residue competition, machinery access and extension gaps as persistent barriers. Custom-hiring centres, farmer groups, local demonstrations, transition-period support and integrated weed-management advice can reduce these constraints, but programmes need to be adapted for small farms and diverse cropping systems. A resilient CA strategy for India should not prescribe a uniform technology package. It should define locally testable options: zero-till or strip-till seeding where suitable; partial or full residue cover based on biomass availability; legume and cover-crop integration where water permits; precision placement of nutrients; and crop rotation appropriate to local markets and risk. In dry areas, practices need to conserve water without creating a residue burden or delaying crop establishment. In irrigated rice systems, water management and residue practices should be assessed jointly because productivity, methane emissions, weed burden and water use can move in different directions.

Table 2: Priority research and reporting improvements for Indian CA evidence

Evidence gap	Recommended standard	Why it matters
Inconsistent yield outcome	Report crop yield, annual system yield, stability and net margin separately	Prevents a gain in one crop from being mistaken for a gain in the whole rotation
Non-equivalent water metrics	Specify irrigation applied, rainfall, ET and exact WUE denominator	Allows valid comparison across irrigated and rainfed studies
SOC concentration reported without stock	Report sampling depth, bulk density and equivalent-soil-mass stock where possible	Reduces bias from changes in soil density and vertical stratification
Weak coverage outside cereal belts	Establish multi-location trials in rainfed pulses, millets, soybean and cotton systems	Improves transferability to central and peninsular India
Short experimental duration	Maintain trials for at least 5–10 years and report transition years separately	Captures learning, soil change, yield stability and cumulative costs
Limited adoption data	Measure residue use, labour, machinery access, weed costs, gendered workload and farmer margins	Connects field performance to real-world adoption and equity

Limitations of the present review

This manuscript synthesizes a focused set of accessible and verified quantitative sources rather than a fully logged systematic search across all subscription databases. It does not report invented screening counts, a PRISMA flow diagram, a formal risk-of-bias score or a newly calculated pooled effect size. The reported numerical estimates come from the original meta-analyses or clearly identified field trials. Some underlying primary studies may be shared between the South Asian and Indian syntheses, and the two meta-analyses use different eligibility criteria; therefore, their estimates are presented side by side and are not combined. The review is consequently best treated as a structured evidence-synthesis draft. To support journal submission under the full title, the author should complete database searches, duplicate screening, extraction of means/standard deviations/sample sizes, overlap checks, risk-of-bias evaluation and a reproducible meta-analysis.

Conclusion

Conservation agriculture offers a credible pathway for improving soil protection and resource-use performance in Indian agriculture, but its benefits depend on the combination of practices and the agroecosystem in which they are applied. Published quantitative syntheses indicate that zero tillage with residue retention can improve yield and water-use efficiency in favourable South Asian settings; an India-focused meta-analysis reports positive average effects on SOC and soil carbon sequestration while finding a small overall yield reduction under its study mix. Long-term Indian field studies show that diversified rotations and

residue management can strengthen system productivity and water productivity, but individual crop responses may remain mixed. The most defensible policy is therefore adaptive rather than uniform: combine reduced disturbance with soil cover, crop diversification, suitable nutrient and weed management, and access to machinery; measure yield, SOC stocks and water outcomes using consistent definitions; and extend multi-year trials beyond the best-studied cereal systems. A fully reproducible, de novo meta-analysis is the next necessary step before these findings are presented as new pooled national estimates.

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