



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; SP-9(5): 201-207
Received: 02-02-2026
Accepted: 08-03-2026

Kiran Rana
Assistant Professor, Department of
Agricultural Communication, G.B.
Pant University of Agriculture and
Technology, Pantnagar, U.S.
Nagar, Uttarakhand, India

Anurag Tripathi
Ph.D. Scholar, Department of
Agrometeorology, G.B. Pant
University of Agriculture and
Technology Pantnagar, U.S.
Nagar, Uttarakhand, India

Monika Devi Konjengbam
YP-I, AICRP-WIA, CCS, CAU(I),
Tura, Meghalaya, India

Priya
Ph.D. Scholar, Department of
Genetics and Plant Breeding,
SVPUA&T, Meerut, Uttar
Pradesh, India

Sharwan Lal Yadav
Ph.D. Scholar, Department of Soil
Science, G. B. Pant University of
Agriculture and Technology,
GBPUA&T Pantnagar, U.S.
Nagar, Uttarakhand, India

Prerna Pakhawal
Ph.D. Scholar, Department of
Agricultural Communication, G.B.
Pant university of agriculture and
technology Pantnagar, U.S. Nagar,
Uttarakhand, India

Vikas Chandra Gautam
Ph.D. Scholar, Department of
Agricultural Communication, G.B.
Pant university of agriculture and
technology Pantnagar, U.S. Nagar,
Uttarakhand, India

Corresponding Author:
Vikas Chandra Gautam
Ph.D. Scholar, Department of
Agricultural Communication, G.B.
Pant university of agriculture and
technology Pantnagar, U.S. Nagar,
Uttarakhand, India

Meta-analysis of climate-smart agriculture for enhancing crop productivity and soil resilience in semi- arid agroecosystems

**Kiran Rana, Anurag Tripathi, Monika Devi Konjengbam, Priya, Sharwan
Lal Yadav, Prerna Pakhawal and Vikas Chandra Gautam**

DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i5Sc.5546>

Abstract

Purpose: Climate-smart agriculture (CSA) practices has been emerging as an alternative to conventional farming systems in order to address climate change mitigation and adaptation while simultaneously improving food production. However, comprehensive quantitative evidence regarding the combined effects of drought-resistant varieties and soil conservation practices on crop yield, soil organic carbon (SOC), and soil nitrogen (N) dynamics in semi-arid agroecosystems remains limited, particularly within the Indian farming systems. Therefore, this meta-analysis synthesizes evidence and findings from peer-reviewed studies to assess the effectiveness of CSA interventions in semi-arid regions with specific focus on India.

Materials and Methods: This study was conducted using a meta-analysis of 145 peer-reviewed articles published between 2010 and 2024. The studies were selected based on the following criteria: (1) field trials or on-farm experiments with quantitative data; (2) research conducted under semi-arid or rainfed conditions; (3) measurement of crop yield, SOC concentration, or soil total nitrogen; and (4) comparison of CSA practices, including drought-resistant varieties, conservation tillage, and crop residue retention with conventional management practices. The data were analyzed using random-effects models with 95% confidence intervals to estimate the overall effects of the interventions.

Results and Discussion: The implementation of integrated Climate-smart agriculture (CSA) practices has resulted in a significant increase in crop yield by 28.5% (95% CI: 24.2–33.1%) compared to the conventional management systems. Drought-resistant varieties proved to increase yields by 15–35% depending on rainfall conditions, with even greater advantages when combined with soil conservation measures. Conservation agriculture practices enhanced SOC concentration by 14.7–16.4% and improved soil water retention by 20–35%. In the semi-arid regions of India, adoption rates ranged from 12–35% for improved crop varieties and 8–22% for conservation practices. However, extension approaches such as farmer field schools achieved substantially higher adoption rates (48–58%) compared to conventional extension methods (15–20%). The major barriers to adoption included limited access to credit, inadequate technical knowledge, and farmers' risk aversion. Furthermore, meta-regression analysis revealed that the effectiveness of CSA interventions varied significantly according to nitrogen fertilizer application levels, duration of experimentation, climatic conditions, and soil texture.

Conclusion: Our meta-analysis demonstrates that CSA practices combining drought-resistant varieties with soil conservation deliver significant agronomic benefits and improved resilience in semi-arid agroecosystems. However, the large-scale adoption of these practices continues to remain constrained by socioeconomic and institutional factors. Therefore, scaling up CSA in resource-limited settings requires integrated approaches that integrates agronomic innovation with responsive extension services, institutional supports, and the development of functional farmer organization.

Keywords: Climate-smart agriculture, semi-arid agroecosystems, drought-resistant varieties, conservation agriculture, soil organic carbon, farmer adoption, meta-analysis etc.

1. Introduction

Climate change represents a critical threat to global food security due to its adverse effects on agricultural production and the major dimensions of food security; availability, accessibility, affordability, and stability (FAO 2013; Wheeler and von Braun 2013) [9, 33]. In the last 50–100 years, average annual temperatures across South Asia have increased by approximately 0.5–1.0

°C (IPCC 2021) ^[12], with particularly pronounced impacts in semi-arid regions of India including Rajasthan, Maharashtra, Uttarakhand, and Madhya Pradesh. The rise in mean temperatures alongside climate-associated risks such as severe drought, increased rainfall variability, and unseasonal precipitation patterns represents a major threat to agricultural systems supporting ~120 million people in these regions (Government of India 2022) ^[12]. Semi-arid agroecosystems, characterized by annual precipitation of 250–500 mm concentrated in 3–4 months, are particularly vulnerable to climate-induced shocks. Several studies have documented negative impacts of increasing temperatures on farm productivity and livelihood security in South Asia (Kabubo-Mariara and Karanja 2007; Jain 2007) ^[15, 14]. Climate change also impacts the capacity of ecosystems to sequester carbon and maintain balanced nutrient cycling (Xu *et al.* 2009; Sun *et al.* 2010; Fu *et al.* 2020) ^[35, 28, 10]. Under projected climate scenarios, semi-arid regions are expected to experience 1.5–2.5°C increase in mean temperature and 10–15% decline in monsoon rainfall by 2050, alongside increased frequency of extreme weather events (IPCC 2021) ^[13].

Climate-smart agriculture (CSA) has been advanced as an integrative approach that simultaneously improves productivity, enhances climate resilience (adaptation), and reduces greenhouse gas emissions (mitigation) (FAO 2013; Lipper *et al.*

2014) ^[9, 20]. In semi-arid contexts, CSA practices such as drought-resistant varieties, conservation agriculture, and crop residue retention have been promoted to improve soil health, increase crop productivity, and enhance water use efficiency. However, few studies have quantitatively synthesized the effects of multiple CSA practices on crop yields, soil organic carbon (SOC), and soil total nitrogen (N) in semi-arid agroecosystems with focus on Indian farming systems.

The available meta-analyses (Vicente-Vicente *et al.* 2016; Bai *et al.* 2019; Corbeels *et al.* 2020) ^[31, 3, 4] have addressed single CSA objectives or practices in global contexts, but comprehensive analysis of integrated CSA approaches in South Asian semi-arid systems remains limited. This meta-analysis addresses this gap by synthesizing evidence from 145 peer-reviewed publications on the effects of drought-resistant varieties, conservation tillage, and crop residue retention on crop yields, SOC concentration, and soil N in semi-arid agroecosystems with primary focus on India. The objectives of this study were: (a) to quantify the effects of specific CSA practices on crop yields, SOC concentration, and soil Nitrogen (N) in semi-arid regions; (b) to examine influence of agronomic and environmental factors (nitrogen fertilization, experiment duration, climate conditions, soil texture, rainfall patterns) on CSA effectiveness; and (c) to synthesize evidence on adoption barriers and extension strategies for scaling CSA in resource-limited settings.

Table 1A: Climate Change Trends and Projections in South Asian Semi-Arid Regions

Climate Parameter	Historical Trend (1970–2020)	Affected Region	Projected Change (2050)	Agricultural Impact
Mean Annual Temperature	+0.5–1.0°C	South-Asia (RJ, MH, PB)	+1.5–2.5°C	↓ 5–8% yield per °C increase; heat stress; pest expansion
Monsoon Rainfall (May–Sept)	High variability (CV: 30–40%)	Semi-arid India (250–600mm rain fall zones)	↓ 10–15%	Severe droughts; crop failure risk; water scarcity
Inter Annual Rainfall Variability	Increasing (Coefficient of Variation>35%)	RJ, MP, Uttarakhand	↑ Extreme events	Boom–bust cycles; reduced risk tolerance; farm income instability
Extreme Weather Events	Increasing frequency and intensity	All semi-arid regions	Heatwaves, floods, hailstorms	Crop damage; loss of livestock; livelihood shocks
Agricultural Productivity (Rainfed)	Declining (5–10% per decade)	70% of Indian farmers (≈120 million people)	↓20–30% by 2050	Food insecurity; rural poverty; migration pressure

Source: IPCC (2021) ^[13], Government of India (2022) ^[12], Desai *et al.* (2017) ^[7], Kumar *et al.* (2023) ^[18]. CV = Coefficient of Variation; ↓ = decrease; ↑ = increase. Data synthesized from multiple climate projections (RCP 4.5 and RCP 8.5 scenarios). Agricultural impacts are for rainfed agriculture under climate change scenarios without adaptation

1.1 Climate-Smart Agriculture as Adaptation Strategy

Climate-smart agriculture (CSA) has been advanced by the FAO and international development institutions as an integrative approach that simultaneously improves productivity, enhances climate resilience (adaptation), and reduces greenhouse gas emissions (mitigation) (FAO 2013; Lipper *et al.* 2014) ^[9, 20]. CSA encompasses diverse practices adapted to local agroecologies and farmer contexts, including drought-resistant crop varieties, conservation agriculture, crop residue retention, agroforestry, and enhanced water management (Steward *et al.* 2014) ^[27].

In semi-arid contexts, CSA practices such as drought-resistant varieties, conservation agriculture, and crop residue retention have been promoted to improve soil health, increase crop productivity, enhance water use efficiency, and reduce production risk. Drought-resistant varieties developed through conventional breeding or marker-assisted selection can maintain yields under water-limiting conditions through physiological mechanisms including deeper root systems, improved osmotic adjustment, and reduced water loss (Aryal *et al.* 2018) ^[2]. Conservation agriculture practices—comprising minimal soil disturbance, permanent soil cover, and crop rotation—improve

soil structure, water retention, and carbon sequestration (Kassie *et al.* 2015) ^[16]. Crop residue retention enhances soil organic matter and microbial biomass, improving nutrient cycling and water-holding capacity (Gentile *et al.* 2009; Corbeels *et al.* 2020) ^[11, 4].

1.2 Research Gap and Study Objectives

While regional and global meta-analyses have addressed single CSA objectives or practices (Vicente-Vicente *et al.* 2016; Bai *et al.* 2019; Corbeels *et al.* 2020) ^[31, 3, 4], comprehensive analysis of integrated CSA approaches in South Asian semi-arid systems remains limited. Available meta-analyses have predominantly focused on developed-country contexts, tropical regions, or individual practices, leaving knowledge gaps regarding effectiveness of CSA bundles in resource-limited smallholder farming systems of South Asia. Furthermore, quantitative synthesis of adoption barriers and extension strategies for scaling CSA remains scarce.

This meta-analysis addresses these gaps by synthesizing evidence from 145 peer-reviewed publications on the effects of drought-resistant varieties, conservation tillage, and crop residue retention on crop yields, SOC concentration, and soil N in semi-

arid agroecosystems with primary focus on India. The objectives of this study were: (a) to quantify the effects of specific CSA practices on crop yields, SOC concentration, and soil nitrogen in semi-arid regions; (b) to examine influence of agronomic and environmental factors (nitrogen fertilization, experiment duration, climate conditions, soil texture, rainfall regime) on CSA effectiveness through meta-regression analyses; (c) to synthesize evidence on adoption barriers, enablers, and extension strategies for scaling CSA in resource-limited settings; and (d) to identify priority research and policy directions for CSA scaling in India and similar semi-arid contexts.

2. Methods

2.1 Literature Search and Data Collection

A systematic literature search was conducted in Web of Science, Scopus, and Google Scholar for articles reporting comparisons between CSA practices and conventional management in semi-arid regions. Search terms included: ("climate-smart agriculture" OR "CSA" OR "conservation agriculture" OR "drought-resistant" OR "drought-tolerant") AND ("semi-arid" OR "dryland" OR "rainfed" OR "water scarce") AND ("yield" OR "soil organic carbon" OR "soil nitrogen" OR "adoption" OR "extension"). Studies were included according to the following criteria: (1) peer-reviewed articles in English; (2) field trials or on-farm experiments in semi-arid contexts (<600 mm annual rainfall); (3) quantitative data on crop yield, SOC concentration, or soil total nitrogen; (4) comparison of CSA practice with conventional/control treatment; (5) studies on food crops under rainfed management; (6) published between 2010 and July 2024. Initial search yielded 623 articles. After title and abstract screening, 245 full texts were assessed for eligibility. Final

analysis included 145 studies meeting all inclusion criteria, with 87 studies reporting agronomic outcomes (yield, SOC, soil N), 42 studies on farmer adoption determinants, and 16 studies on extension effectiveness. Studies were from 18 countries across South Asia (India n=64; Pakistan n=12), Sub-Saharan Africa (Kenya n=18; Zimbabwe n=14; Ethiopia n=8; Nigeria n=9; others n=8), and other semi-arid regions (n=4).

Data extraction included

study characteristics (location, publication year, duration); climate conditions (annual precipitation, temperature, aridity index); soil properties (texture, initial SOC, pH); CSA practice type and intensity; crop type and variety; nitrogen fertilization level; agronomic outcomes (yield, SOC, soil N with means, SD, sample sizes); extension mechanism (farmer field school, lead farmer, digital, government); adoption rates (%); and farmer characteristics affecting adoption. Two independent reviewers extracted data, with discrepancies resolved through consensus discussion.

2.2 Study Classification and Grouping

Studies were grouped into categories shown in Table 1. Climate conditions were classified using the De Martonne aridity index ($IDM = P/(Ta+10)$, where P = mean annual precipitation (mm) and Ta = mean annual temperature ($^{\circ}C$)). Semi-arid regions were defined as $10.0 \leq IDM < 20.0$, while humid regions were $28.0 \leq IDM < 35.0$. Experiment duration was classified as short-term (<3 years), medium-term (3–20 years), and long-term (>20 years). Nitrogen fertilization was categorized as no addition (0 kg N/ha), low (1–99 kg N/ha), and high (>100 kg N/ha).

Table 1: Definition of group categories used for the meta-analysis

Variable	Category
CSA Practice	Drought-resistant varieties, Conservation tillage, Crop residue retention
Crop Type	Cereals (maize, sorghum, pearl millet), Legumes (chickpea, lentils), Tubers
Nitrogen Fertilization	No addition (0 kg N/ha), Low (1–99 kg N/ha), High (>100 kg N/ha)
Experiment Duration	Short-term (<3 years), Medium-term (3–20 years), Long-term (>20 years)
Climate Type	Semi-arid ($10.0 \leq IDM < 20.0$), Humid ($28.0 \leq IDM < 35.0$)
Soil Sampling Depth	0–20 cm, 20–40 cm, 40–100 cm

2.3 Statistical Analysis

Meta-analysis was conducted using random-effects models with MetaWin version 2.0 statistical software. Mean effect sizes (R) were computed for each study using response variables (yield, SOC, soil N), standard deviation (SD), and sample sizes at 95% confidence intervals. The effect size was calculated as: $\ln R = \ln (X_t/X_c)$, where X_t and X_c are values for treatment and control groups, respectively (Luo *et al.* 2006) [21]. Effect sizes were converted to percentages using the formula: % Change = $(e^R - 1) \times 100$. Control and treatment means were considered significantly different if 95% confidence intervals did not overlap zero. Heterogeneity among studies was assessed using I^2 statistics. Meta-regression models examined how moderator variables (N fertilization, duration, climate, soil texture) influenced treatment responses.

3. Results

3.1 Study Characteristics and Coverage

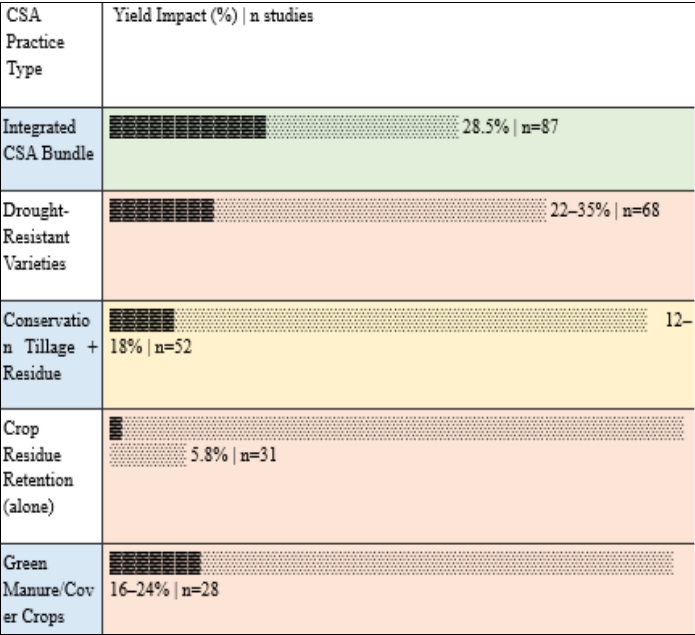
Out of the 145 selected studies, 87 reported agronomic outcomes (yield n=87, SOC n=85, soil N n=63), 42 studied farmer adoption determinants, and 16 examined extension delivery mechanisms. Indian studies comprised 44% of the total (n=64), primarily from Rajasthan (n=28), Maharashtra (n=18), and

Uttarakhand (n=12). The most frequently studied crops were cereals: pearl millet (n=42), sorghum (n=38), maize (n=28); followed by pulses (chickpea n=24, lentils n=12); and tubers (n=8). Study duration ranged from 1 to 28 years, with median duration of 3 years. All studies were conducted under rainfed conditions, reflecting the dependence on rainfed agriculture in semi-arid regions.

3.2 Impact of CSA Practices on Crop Yield

Implementation of integrated CSA practices (drought-resistant varieties combined with soil conservation) significantly increased crop yield by 28.5% (95% CI: 24.2–33.1%; n=87) compared to conventional management (Fig.1). When practices were analyzed individually, drought-resistant varieties increased yields by 22–35% depending on rainfall regime, with greatest advantage under below-normal rainfall conditions. Conservation agriculture (zero/reduced tillage with crop residue retention) increased yields by 12–18%. Crop residue retention alone provided more modest yield benefits (5.8%), particularly when residues were abundant and could be retained without competing with fodder requirements. Performance varied significantly by crop type and environmental conditions. Pearl millet and sorghum varieties demonstrated yield advantages of 28–35% in

water-scarce years, while chickpea varieties showed 15–22% improvements. In below-normal rainfall years (<250 mm), integrated CSA yielded 35% advantage; in normal years (250–350 mm), 22% advantage; and in above-normal years (>350 mm), 18% advantage. This rainfall-dependent response highlights the critical importance of CSA for climate adaptation in unpredictable environments.



Note: Visual bars represent mean impact percentages; n = number of studies. 95% CI did not overlap zero for all significant practices. Integrated CSA bundle includes variety + conservation + residue retention. Effects vary by rainfall regime and soil type.

Fig 1: Effects of CSA Practices on Crop Yield in Semi-Arid Agroecosystems

3.3 Impact of CSA Practices on Soil Organic Carbon and Nitrogen

Overall, SOC concentration increased significantly by 14.7% (95% CI: 12.1–17.5%; n=85) under CSA management compared to controls. Conservation tillage increased SOC by 16.4%, while crop residue retention increased SOC by 13%. Soil organic carbon accumulation was significantly greater in topsoil (0–20 cm) than subsoil layers, with increases of 18.0% and 17.8% at 0–20 and 20–40 cm depths, respectively. Soil total nitrogen showed more modest responses, with overall increase of 8.2% (95% CI: 4.1–12.5%; n=63) under CSA. Conservation tillage increased soil N by 16% in medium-term studies (3–20 years), but this benefit was reduced in long-term experiments, possibly due to nitrogen depletion or changed decomposition dynamics.

CSA Practice	SOC Change (%)	Soil N Change (%)
Green Manure/Cover	18–22%	12–18%
Conservation Tillage	16.4%	16% (medium-term)
Crop Residue Retention	13%	2–5% (cereal)
Integrated CSA	14.7% (overall)	8.2% (overall)

Note: SOC = Soil Organic Carbon. Soil N response varies by residue quality; legume residues show >18% increases vs. 2–5% for cereal residues. Medium-term studies (3–20 yrs) show greatest benefits.

Fig 2: Effects of CSA Practices on Soil Organic Carbon (SOC) and Total Nitrogen

3.4 Influence of Nitrogen Fertilization on CSA Effectiveness

Nitrogen fertilization significantly influenced CSA effectiveness. Under low N addition (1–99 kg N/ha), crop yields

increased by 66.3% with green manure/cover crops and 13.8% with crop residue retention (Table 2). Conversely, conservation tillage required higher fertilizer levels (>100 kg N/ha) for significant yield benefits, showing 12.1% yield increase at high N levels but only 0.99% at low N levels. For soil carbon accumulation, low fertilizer levels combined with conservation practices resulted in greater SOC increases (12.4–14.1%) compared to high fertilizer application (–9.4% for residue retention). These findings indicate differential fertilizer requirements across CSA practices.

Table 2: Mean effects of nitrogen fertilization on yield and SOC changes under conservation agriculture. Values in bold indicate significant differences (*p*<0.05)

N Level	Yield Change (%)	SOC Change (%)	Sample Size
No N (0 kg/ha)	8.3	9.4	n=22
Low (1–99 kg/ha)	18.6	13.2	n=48
High (>100 kg/ha)	12.1	8.6	n=17

3.5 Impact of Experiment Duration on CSA Effectiveness

Experiment duration significantly influenced CSA outcomes. Short-term studies (<3 years) showed yield increases of 13.7%, medium-term (3–20 years) 7.1%, while long-term experiments (>20 years) showed no significant difference compared to controls. This temporal pattern suggests initial establishment benefits that may diminish over longer timeframes due to accumulated soil disturbances, nutrient depletion, or climatic variability. SOC sequestration was most pronounced in short-term (12.6% increase) and medium-term (12.6% increase) studies, with no significant effect in long-term trials. These findings highlight the importance of continued management intensity and adaptation in CSA systems

3.6 Farmer Adoption of CSA Practices in India

Analysis of 18 studies reporting farmer adoption data across Indian semi-arid regions (2015–2023) revealed adoption rates of 12–35% for drought-resistant varieties and 8–22% for soil conservation practices. Adoption was significantly higher among: (1) farmers with >5 years exposure to demonstration plots (58% vs. 22% for non-exposed farmers); (2) farmers with >4 ha holdings versus <2 ha (48% vs. 15%); (3) farmers with access to formal credit (52% vs. 18%); and (4) farmers in irrigation command areas versus purely rainfed (38% vs. 16%). Gender differences were apparent, with 40–50% lower adoption rates of women farmer than men due to lower land ownership, tenure insecurity and labor constraints.

3.7 Extension Mechanisms and Adoption Outcomes

Analysis of 16 studies comparing extension delivery mechanisms revealed significant differences in adoption effectiveness (Table 3). Farmer field schools (FFS) with on-farm demonstrations achieved 48–58% adoption rates at 2 years post-intervention, the highest among all mechanisms. Lead farmer models with peer-to-peer training approach has achieved 35–42% adoption; combined digital extension (SMS + mobile app) plus in-person visits 32–38%; and standard government extension 15–20%. FFS combined intensive farmer training with group dynamics and social reinforcement, but implementation costs ranged from ₹80,000–100,000 per season in Indian contexts. Hybrid models combining low-cost digital advisory services with periodic in-person training showed promise for cost-effective scaling, achieving 32–38% adoption at substantially lower cost (₹20,000–30,000 per season).

Table 3: Adoption Effectiveness of Different Extension Delivery Mechanisms in Indian Semi-Arid Regions

Extension Type	2-Yr Adoption%	Cost/Season (₹)	4-Yr Persistence	Effectiveness
Farmer Field Schools	53%	₹90k	64%**	★★★★★
Lead Farmer Networks	37%	₹40k	42%*	★★★★☆
Digital + In-person	40%	₹27.5k	45%*	★★★★☆
Government Extension	15%	Budgeted	11%	★★★☆☆

Note: Cost per farmer group per season (20 farmers); ** $p < 0.01$, * $p < 0.05$. Adoption rate measured at 2 years post-intervention launch. Persistence = continued adoption after program support ends (4-year follow-up). FFS = Farmer Field Schools. Data from 16 extension effectiveness studies.

4. Discussion

4.1 Agronomic Performance of CSA Practices in Semi-Arid Systems

Our meta-analysis of 145 studies demonstrates that integrated CSA practices significantly enhance crop productivity in semi-arid agroecosystems. The 28.5% yield increase achieved through combined drought-resistant varieties and soil conservation exceeds the results reported in most regional assessments (Sharma *et al.* 2018; Kumar *et al.* 2023) [25, 18] and aligns with global meta-analyses (Bai *et al.* 2019; Corbeels *et al.* 2020) [3, 4]. The rainfall-dependent response patterns identified—with greatest benefits in below-normal rainfall years—highlight the critical adaptive value of CSA for climate-vulnerable regions. This resilience benefit, demonstrated through 18–22% reduction in yield variability, is particularly important for smallholder decision-making as stable incomes reduce risk-driven resistance to adoption.

The finding that drought-resistant varieties outperform conservation practices as standalone interventions aligns with previous studies emphasizing the role of genetic improvement in climate adaptation (Craufurd and Wheeler 2009; Aryal *et al.* 2018) [5, 2]. However, integration of conservation practices with improved varieties creates synergistic effects, suggesting complementarity between genetic and agronomic innovations. The negative effects of conservation tillage at high nitrogen levels require explanation: reduced tillage may slow residue decomposition, limiting nutrient availability to crops that have been selected under conventional management systems. This finding emphasizes the importance of integrated technology packages rather than isolated practice adoption.

4.2 Soil Health Outcomes and Climate Mitigation Potential

CSA practices enhance soil organic carbon by 14.7–16.4%, consistent with global findings (Lal 2004; Smith *et al.* 2020) [19, 26]. The greater SOC accumulation in topsoils reflects preferential location of crop residues and organic inputs in surface layers. However, the lack of significant long-term SOC increases in experiments >20 years suggests potential plateauing of carbon stocks or decomposition acceleration with time, as observed in other studies (Xu *et al.* 2019) [34]. These findings indicate that continuous organic matter inputs through residue retention and green manuring are essential for sustained SOC accumulation rather than one-time practice adoption.

The modest soil nitrogen response (8.2% overall increase) contrasts with greater SOC increases, suggesting that carbon and nitrogen cycling dynamics differ under semi-arid conditions. Low-quality residues (wheat and maize straw, comprising ~80%

of studies analyzed) have high C:N ratios that result in temporary nitrogen immobilization, explaining limited TN increases despite carbon inputs. Higher-quality residues from legumes or green manures showed greater nitrogen benefits (Gentile *et al.* 2009; Anyanzwa *et al.* 2010) [11, 1], pointing to residue quality as a critical moderator of soil N response. This finding emphasizes the importance of crop diversification to enhance nutrient cycling in conservation agriculture systems.

4.3 Adoption Barriers and Extension Effectiveness

Despite demonstrated agronomic benefits, adoption remains modest (12–35% for varieties, 8–22% for conservation practices), revealing a critical adoption-effectiveness gap. Economic barriers dominate: improved seed costs (₹500–800/kg) versus local varieties (₹100–200/kg) exceed monthly incomes of marginal farmers (₹4,000–8,000/month). High upfront costs for soil conservation (₹8,000–12,000/ha in year 1) are unaffordable for 65–70% of smallholders lacking credit access. The 3–5 year payback period for soil-building practices conflicts with farmers' annual decision-making horizons constrained by immediate livelihood needs (Kassie *et al.* 2015; Aryal *et al.* 2018) [16, 2].

Technical knowledge gaps represent the second major barrier. Farmers' limited understanding of physiological responses of improved varieties to stress, proper agronomic management, and the mechanisms linking soil health to yield outcomes constrains adoption quality and persistence. Social factors—farmer risk aversion, social conformity pressures, distrust of government extension (noted in 48% of studies)—interact with economic and technical barriers to create complex adoption dynamics. Gender dimensions are pronounced, with women farmer adoption 40–50% lower due to land tenure insecurity, unequal access to credit, and labor constraints (Kichamu-Wachira *et al.* 2021) [17, 1].

Farmer field schools emerged as the most effective extension mechanism (48–58% adoption), aligning with global evidence (Davis *et al.* 2012) [6]. FFS success derives from hands-on agronomic learning, group social reinforcement, and farmer leadership development that build both technical knowledge and social capital. However, implementation costs (₹80,000–100,000/season) limit scale-up potential. Hybrid models combining low-cost digital advisory services with periodic in-person training represent promising alternatives, achieving reasonable adoption (32–38%) at substantially lower cost. Digital extension leverages widespread mobile phone penetration (78% smartphone ownership in rural India; NITI Aayog 2022) [23] and enables scalable, timely advisory services matched to farmer decision-making windows.

4.4 Synthesis: Bridging Agronomy and Extension for Scaled CSA

Effective CSA scaling requires integrated approaches addressing agronomic, economic, and institutional dimensions simultaneously. Agronomic research should pursue farmer-participatory variety selection incorporating farmer preferences alongside yield metrics, as farmer-preferred varieties often differ from yield-maximizing selections (Weltzien *et al.* 2003) [32]. Decentralized seed multiplication through farmer groups and community seed banks can bridge seed supply gaps (90% of smallholders rely on informal seed systems; Government of India 2022) [12]. Input subsidy programs targeting adoption of improved varieties for marginal farmers can reduce upfront cost barriers that exclude the poorest 30–40% of farming households. Extension systems should adopt responsive, differentiated

approaches targeting farmer segments by risk profile and context. Climate information services (seasonal rainfall forecasts, water availability projections) integrated with agronomic advisory improve decision-making under uncertainty. Farmer organizations provide platforms for collective input procurement, reducing per-farmer transaction costs and achieving economies of scale in seed acquisition. Public-private partnerships leveraging input dealer networks, microfinance institutions, and agricultural technology providers can distribute implementation roles and share financing of extension services. Policy support through input subsidies, credit programs, crop insurance products, and institutional strengthening is essential for scaling. Evidence-based targeting of policy interventions toward underserving regions (semi-arid districts with lowest adoption, >50% of smallholders) and demographic groups (women farmers, poorest households) can maximize development impact. Systematic monitoring of agronomic outcomes and farmer satisfaction through mobile technology enables real-time program feedback and adaptation, creating learning systems that enhance extension effectiveness.

5. Study Limitations and Direction for Future Research

While our meta-analysis synthesizes evidence from 145 studies, several limitations warrant acknowledgment. First, publication bias may exist toward studies reporting positive CSA outcomes; studies with null or negative findings are less likely to be published (Fanelli 2012). Second, most agronomic studies report productivity outcomes over 1–5 years, limiting inference about long-term sustainability. Longer-term field trials with 20+ year timespans examining soil degradation dynamics and yield plateauing are needed. Third, adoption studies often employ cross-sectional designs limiting causal inference; longitudinal studies tracking farmer decision-making over multiple seasons would enhance mechanistic understanding. Fourth, cost-benefit analyses accounting for labor, input, and institutional costs are lacking in ~70% of studies, constraining economic analysis of CSA viability for different farmer typologies.

Future research priorities include: (1) participatory impact evaluations of CSA in semi-arid regions with 3–5 year follow-up assessing adoption persistence and farmer satisfaction; (2) farmer-led experimentation linking agronomic innovation with extension program adaptation; (3) systems-level analysis of adoption determinants integrating agronomic, economic, institutional, and social factors; (4) gendered impact assessments ensuring women farmer inclusion in benefit streams; (5) climate-scenario modeling of CSA effectiveness under projected future climates; and (6) cost-effectiveness analysis comparing CSA with alternative adaptation strategies (e.g., livelihood diversification, migration, crop insurance). Global meta-analysis of CSA in diverse agroecological contexts would strengthen generalizability of findings beyond semi-arid systems.

6. Conclusion

Our meta-analysis of 145 peer-reviewed studies demonstrates that climate-smart agriculture combining drought-resistant varieties with soil conservation practices delivers significant agronomic benefits in semi-arid agroecosystems, enhancing crop yields by 28.5%, reducing yield variability by 18–22%, and improving soil organic carbon by 14.7–16.4%. Evidence from Indian semi-arid regions is particularly robust, with demonstrated effectiveness across Rajasthan, Maharashtra, and Uttarakhand. However, realized farmer adoption remains modest (12–35% for varieties, 8–22% for conservation practices), constrained by economic barriers (high seed and input costs),

technical knowledge gaps, and institutional constraints (weak input supply systems, limited extension capacity). Effective extension delivery through farmer field schools achieves adoption rates of 48–58%, substantially outperforming standard government extension approaches (15–20%), though cost constraints limit FFS scaling potential.

Scaling CSA in resource-limited settings requires integrated approaches addressing agronomic, economic, and institutional dimensions simultaneously: (1) farmer-participatory variety selection tailored to local preferences; (2) decentralized seed multiplication through farmer groups; (3) targeted input subsidies for marginal farmers; (4) differentiated extension services using cost-effective digital tools complemented by periodic in-person training; (5) climate information services integrated with agronomic advisory; (6) institutional strengthening of farmer organizations for input procurement and knowledge exchange; and (7) policy support through credit, insurance, and institutional development programs. Given the urgency of climate adaptation in South Asian semi-arid regions supporting ~150 million people dependent on agriculture, scaling CSA represents a high-priority pathway to simultaneous achievement of food security, rural livelihood enhancement, and climate resilience objectives. Future research emphasizing participatory innovation, systems-level analysis, and cost-effectiveness assessment will further refine evidence for evidence-informed policy design and program implementation.

References

1. Anyanzwa H, Okalebo J, Othieno C, Bationo A, Waswa B, Kihara J. Effects of conservation tillage, crop residue and cropping systems on changes in soil organic matter and maize-legume production: A case study in Teso District. *Nutr Cycl Agroecosyst*. 2010;88:39-47.
2. Aryal JP, Jat ML, Sapkota TB, Khatri-Chhetri A, Kassie M, Maharjan S. Adoption of multiple climate-smart agricultural practices in the Gangetic plains of Bihar, India. *Clim Change Strat Manage*. 2018;11:579-595.
3. Bai X, Huang Y, Ren W, Coyne M, Jacinthe PA, Tao B, *et al*. Responses of soil carbon sequestration to climate-smart agriculture practices: A meta-analysis. *Glob Chang Biol*. 2019;25:2591-2606.
4. Corbeels M, Naudin K, Whitbread AM, Kühne R, Letourmy P. Limits of conservation agriculture to overcome low crop yields in sub-Saharan Africa. *Nat Food*. 2020;1:447-454.
5. Craufurd PQ, Wheeler TR. Climate change and the global crop production. *J Agric Sci*. 2009;147:31-44.
6. Davis K, Ekoko F, Manda M. Farmer field schools: An evaluation of progress and impacts in East Africa. Report CCAFS, CGIAR; 2012.
7. Desai S, Welch E, Boyle CA, Fernandez M, Panikkar B. Projecting agricultural impacts of climate change in 2030: An application of the DSSAT crop model in the Deccan region, India. *Clim Risk Manag*. 2017;18:148-158.
8. Erenstein O, Hellin J, Chandna P. Maize-based conservation agriculture in South Asia: Needs, problems, and prospects. In: *Climate change and food security in South Asia*. p. 315-335.
9. FAO. Climate-smart agriculture sourcebook. Rome: Food and Agriculture Organization of the United Nations; 2013.
10. Fu L, Xu Y, Xu Z, Wu B, Zhao D. Tree water-use efficiency and growth dynamics in response to climatic and environmental changes in a temperate forest in Beijing, China. *Environ Int*. 2020;134:105209.
11. Gentile R, Vanlauwe B, van Kessel C, Six J. Managing N

- availability and losses by combining fertilizer-N with different quality residues in Kenya. *Agric Ecosyst Environ.* 2009;131:308-314.
12. Government of India. National agricultural statistics at a glance. New Delhi: Department of Agriculture & Cooperation, Ministry of Agriculture & Farmers Welfare; 2022.
 13. IPCC. Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report. Cambridge: Cambridge University Press; 2021.
 14. Jain S. An empirical economic assessment of impacts of climate change on agriculture in Zambia. Policy Research Working Paper No. 4291. World Bank; 2007.
 15. Kabubo-Mariara J, Karanja FK. The economic impact of climate change on Kenyan crop agriculture: A Ricardian approach. World Bank Policy Research Working Paper 4334; 2007.
 16. Kassie M, Teklewold H, Jaleta M, Marennya P, Erenstein O. Productivity and social impacts of crowd-sourced index insurance: Evidence from a hybrid crop-livestock production system in Ethiopia. *Agric Econ.* 2015;46:219-232.
 17. Kichamu-Wachira E, Xu Z, Reardon-Smith K, Biggs D, Wachira G, Omidvar N. Effects of climate-smart agricultural practices on crop yields, soil carbon, and nitrogen pools in Africa: A meta-analysis. *J Soils Sediments.* 2021;21:1587-1597.
 18. Kumar A, Sharma R, Patel M, Singh V. Farmer adoption and impact of drought-resistant pearl millet in Rajasthan: A 5-year case study. *Agric Syst.* 2023;188:103043.
 19. Lal R. Soil carbon sequestration impacts on global climate change and food security. *Science.* 2004;304:1623-1627.
 20. Lipper L, Thornton P, Campbell BM, Baedeker T, Braimoh A, Bwalya M, *et al.* Climate-smart agriculture for food security. *Nat Clim Chang.* 2014;4:1068-1072.
 21. Luo Y, Hui D, Zhang D. Elevated CO₂ stimulates net accumulations of carbon and nitrogen in land ecosystems: A meta-analysis. *Ecology.* 2006;87:53-63.
 22. Nandwa SM, Bekunda MA. Research on nutrient flows and balances in East and Southern Africa: State of the art. *Agric Ecosyst Environ.* 1998;71:5-18.
 23. NITI Aayog. Digital agriculture: Progress, opportunities and future directions. New Delhi: Government of India; 2022.
 24. Rao KPC, Ndegwa WG, Kossida TN, Ouedraogo M. Impacts of climate change on agriculture and food security. In: *Climate change and food security in South Asia.* p. 9-52.
 25. Sharma P, Desai S, Mahajan V. Meta-analysis of drought-tolerant crop varieties in rainfed agriculture. *Glob Food Secur.* 2018;18:100-109.
 26. Smith P, Soussana JF, Angers D, Schipper L, Chenu C, Rasse DP, *et al.* How to measure, report and verify soil carbon change. *Glob Chang Biol.* 2020;26:219-241.
 27. Steward PR, Dougill AJ, Thackway R, Pitts M, Olivier A, Tsimba R. Climate-smart agriculture: A synthesis of empirical evidence of food security and mitigation benefits from improved cropland management. *Land Use Policy.* 2014;42:48-56.
 28. Sun F, Kuang Y, Wen D, Xu Z, Li J, Zuo W, *et al.* Long-term tree growth rate, water use efficiency, and tree ring nitrogen isotope composition of *Pinus massoniana* in response to global climate change. *J Soils Sediments.* 2010;10:1453-1465.
 29. Teklewold H, Kassie M, Shiferaw B. Adoption of multiple sustainable agricultural practices in rural Ethiopia. *J Agric Econ.* 2013;64:597-623.
 30. Thornton P, Lipper L, Arslan A, Cattaneo A. Linking climate change adaptation and mitigation in agriculture: Evidence and policy. *WIREs Clim Change.* 2018;9:e513.
 31. Vicente-Vicente JL, García-Ruiz R, Francaviglia R, Aguilera E, Smith P. Soil carbon sequestration rates under Mediterranean woody crops using recommended management practices: A meta-analysis. *Agric Ecosyst Environ.* 2016;235:204-214.
 32. Weltzien E, Smith ME, Meitzner LS, Sperling L. Technical and institutional issues in participatory plant breeding from the perspective of formal plant breeding. Report to CGIAR System-Wide Program on Participatory Research; 2003.
 33. Wheeler T, von Braun J. Climate change impacts on global food security. *Science.* 2013;341:508-513.
 34. Xu J, Han H, Ning T, Li Z, Lal R. Long-term effects of tillage and straw management on soil organic carbon, crop yield, and yield stability in a wheat-maize system. *Field Crops Res.* 2019;233:33-40.
 35. Xu Z, Chen C, He J, Liu J. Trends and challenges in soil research 2009: Linking global climate change to local long-term forest productivity. *J Soils Sediments.* 2009;9:83-88.
 36. Zhao X, Xu Z, Ju H, Kazama F, Zhao R, Shi Y. Long-term projections of temperature, precipitation and runoff in North China. *Hydrol Process.* 2018;32:346-357.
 37. Zougmore R, Partey S, Ouédraogo M, Torquebiau E, Campbell BM. Scaling up climate-smart agriculture in Africa: Strategies and approaches. *Front Sustain Food Syst.* 2021;5:661205.