



REVIEW ARTICLE

Climate-smart agronomic practices in millet systems: A review of productivity, adaptation and resource-use efficiency

A M Juno¹, M A Vennila^{2*}, A Janaki Rani¹, S Kokilavani³ & R Gangai Selvi⁴

¹Department of Agricultural Extension and Rural Sociology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

²ICAR-Krishi Vigyan Kendra, Papparpatty, Dharmapuri 636 809, Tamil Nadu, India

³Agro Climate Research Centre, Directorate of Crop Management, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

⁴Department of Physical Sciences and Information Technology, Agricultural Engineering College and Research Institute, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Correspondence email - vennila.ma@tnau.ac.in

Received: 18 April 2026; Accepted: 20 May 2026; Available online: Version 1.0: 30 June 2026

Cite this article: Juno AM, Vennila MA, Janaki RA, Kokilavani S, Gangai SR. Climate-smart agronomic practices in millet systems: A review of productivity, adaptation and resource-use efficiency. Plant Science Today. 2026;13(sp2):01–18. <https://doi.org/10.14719/pst.15076>

Abstract

Millet-based farming systems are central to food and livelihood security in semi-arid regions facing increasing climate variability. Climate-smart agriculture (CSA) has gained prominence as a strategic approach to enhance productivity, strengthen adaptive capacity and improve environmental sustainability in these systems. This review synthesises evidence from 80 peer-reviewed studies (2015–25), including 58 works cited directly to support key findings. A systematic review was conducted following PRISMA guidelines, supported by bibliometric and thematic analyses. The findings show that CSA interventions particularly soil-water conservation, nutrient management, improved varieties and crop diversification consistently enhance yield stability, water-use efficiency and drought resilience. Integrated CSA approaches demonstrate more robust and consistent outcomes than single interventions. Nonetheless, mitigation effects remain insufficiently quantified across the literature. Adoption of CSA practices is shaped by access to inputs, extension services, market linkages and institutional support, which continue to constrain large-scale implementation. The results indicate that while agronomic technologies are effective, their broader impact is limited by systemic barriers related to institutions and value chains. The study underscores the need for integrated strategies that combine technological, institutional and market interventions to improve the sustainability and scalability of millet-based CSA systems. Overall, this review provides a comprehensive synthesis of existing evidence and identifies key research and policy priorities for advancing climate-resilient millet agriculture.

Keywords: adaptation; climate-smart agriculture; millets; productivity; resource-use efficiency; smallholder adoption

Introduction

Millet-based agro-ecosystems underpin the food security and livelihoods of millions of smallholder farmers across semi-arid regions of South Asia and sub-Saharan Africa. These regions are characterised by erratic rainfall, low soil fertility and high climatic variability (1–3). Millets, including pearl millet, finger millet and other small millets like foxtail millets, kodo millet, barnyard millet, are inherently adapted to these stress-prone environments due to their C₄ photosynthetic pathway, short growing duration and tolerance to drought and marginal soils (4–7). These traits position millets as critical crops for climate-resilient agriculture under increasing climate variability (8–10).

Despite these ecological advantages, millets experienced a prolonged period of neglect during the Green Revolution, which prioritised irrigated cereals such as rice and wheat (10, 11). This shift resulted in reduced research investment, weak value chains and declining cultivation of millets in several regions (2, 8). However, renewed global attention, particularly through initiatives such as the International Year of Millets, has repositioned millets as climate-

resilient “nutri-cereals” capable of addressing food security, nutritional deficiencies and climate adaptation challenges simultaneously (12–14).

Within this context, climate-smart agriculture (CSA) has emerged as a framework aimed at enhancing productivity, strengthening adaptation and improving environmental sustainability (15, 16). The CSA is a context-specific, systems-based approach that integrates agronomic practices, institutional arrangements and farmer decision-making (17, 18). Millet-based systems are particularly relevant within this framework, as they are predominantly rainfed, resource-constrained and highly exposed to climatic risks (3, 19).

From a biophysical perspective, millet systems exhibit strong alignment with CSA objectives. Advances in stress-tolerant varietal development, including genomics-driven breeding and trait-based selection, have enhanced adaptive capacity under drought and heat stress (4, 20, 21). Agronomic interventions such as conservation agriculture, residue retention, fertiliser microdosing and integrated nutrient management have demonstrated improvements in yield stability and resource-use efficiency (22–24). Crop diversification and

intercropping systems, particularly millet-legume combinations, further contribute to productivity enhancement, soil fertility improvement and risk reduction (24, 25). In addition, process-based crop modelling approaches, including Decision Support System for Agrotechnology Transfer (DSSAT) and AquaCrop, have improved understanding of millet performance under varying climatic and management scenarios (26–28).

However, the effectiveness of CSA interventions in millet systems remains highly context-dependent and often depends on combinations of practices rather than isolated technologies. Recent studies increasingly emphasise integrated CSA bundles combining varietal improvement, nutrient management and water conservation, as these approaches tend to produce more stable outcomes than isolated interventions (14, 22, 29). However, evidence remains fragmented across agronomic, institutional and adoption dimensions. At the same time, important trade-offs persist, as increased productivity does not always translate into higher net income due to rising input costs and labour requirements (2, 30).

Beyond biophysical performance, adoption of CSA practices in millet systems is strongly influenced by socio-economic and institutional factors. Access to inputs, credit, extension services and markets plays a critical role in shaping farmer decision-making (9, 31). Empirical studies show that education, farm size, climate-risk perception and institutional access are key drivers of adoption, while labour constraints, financial limitations and weak value chains act as major barriers (18, 32–35). These constraints limit the scalability of otherwise effective CSA technologies and highlight the need to analyse millet systems as integrated socio-ecological systems rather than purely agronomic units (3).

Despite a growing body of literature, research remains fragmented across disciplinary silos, limiting integrative understanding of cross-scale interactions between technology, behaviour and institutions (15). Most studies focus on individual technologies or specific outcomes, with limited integration across productivity, adaptation, mitigation and adoption dimensions. Furthermore, millet-specific analyses are often embedded within broader cereal studies, obscuring their distinct ecological and institutional characteristics (8, 11). As a result, there is a lack of system-level synthesis that captures interactions between technological performance, farmer behaviour and institutional structures.

This fragmentation suggests that constraints in millet-based CSA systems arise less from technological limitations and more from coordination failures across biophysical, institutional and market domains. Addressing these challenges requires an integrated analytical approach that links technological, socio-economic and policy dimensions within a unified framework.

To address this gap, the present review applies a combined theory, context, characteristics and methodology (TCCM) framework and water-smart, nutrient-smart, carbon-smart, weather-smart, knowledge-smart and related categories (SMART) functional classification to systematically synthesise evidence on CSA in millet-based agro-ecosystems. The TCCM framework enables structured analysis of how research is conceptualised, contextualised and methodologically executed, while the SMART classification categorises CSA practices based on their functional roles in productivity, adaptation and mitigation (16). By integrating these approaches, this study aims to provide a system-level understanding of millet-based CSA.

Based on a synthesis of 80 empirical studies published between 2015 and 2025, the objectives of this review are to: (1) analyse the evolution and structure of millet-CSA research; (2) classify CSA practices and evaluate their impacts on yield, income, resilience and environmental outcomes and (3) identify key socio-economic, institutional and methodological constraints influencing the transition towards climate-resilient millet-based agro-ecosystems.

Materials and Methods

Literature search and study selection

A systematic literature search was conducted following the PRISMA 2020 guidelines to identify peer-reviewed empirical studies on CSA in millet-based production systems (36). Four major databases—Scopus, ScienceDirect, Springer Nature and Google Scholar were searched to ensure broad disciplinary coverage across agronomy, environmental sciences and socio-economic research domains. The review period was restricted to 2015–25 to capture the contemporary phase of CSA research in millet systems.

Search strings combined CSA-related terms (“climate-smart agriculture”, “climate-resilient agriculture”, “sustainable intensification”, “conservation agriculture”) with millet-specific keywords (“millet”, “pearl millet”, “finger millet”, “foxtail millet”, “small millets”, “sorghum”) and outcome indicators (“yield”, “income”, “productivity”, “adoption”, “resilience”, “water-use efficiency”) (Table 1). Full database-specific search strings are provided in Supplementary Table 1.

An initial search identified 1252 records (Fig. 1). After removing duplicates ($n = 178$), 1074 titles and abstracts were screened, resulting in the exclusion of 656 records. A total of 418 full-text articles were assessed for eligibility, of which 338 were excluded due to lack of CSA focus, absence of millet-specific analysis, non-empirical design or incomplete outcome reporting. The final dataset comprised 80 empirical studies for qualitative synthesis. A subset of

Table 1. Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
• Empirical studies explicitly addressing CSA technologies or practices • Studies conducted on millet or millet-based systems • Studies reporting at least one productivity, income, resilience or environmental outcome • Articles published in peer-reviewed journals (2015–25) • Field experiments, farm surveys, modelling studies or mixed-methods research	• Non-CSA or generic climate studies • Studies not focused on millets • Reviews, editorials, commentaries and conceptual papers without empirical results • Studies lacking yield, income, resilience or impact metrics

CSA: climate smart agriculture.

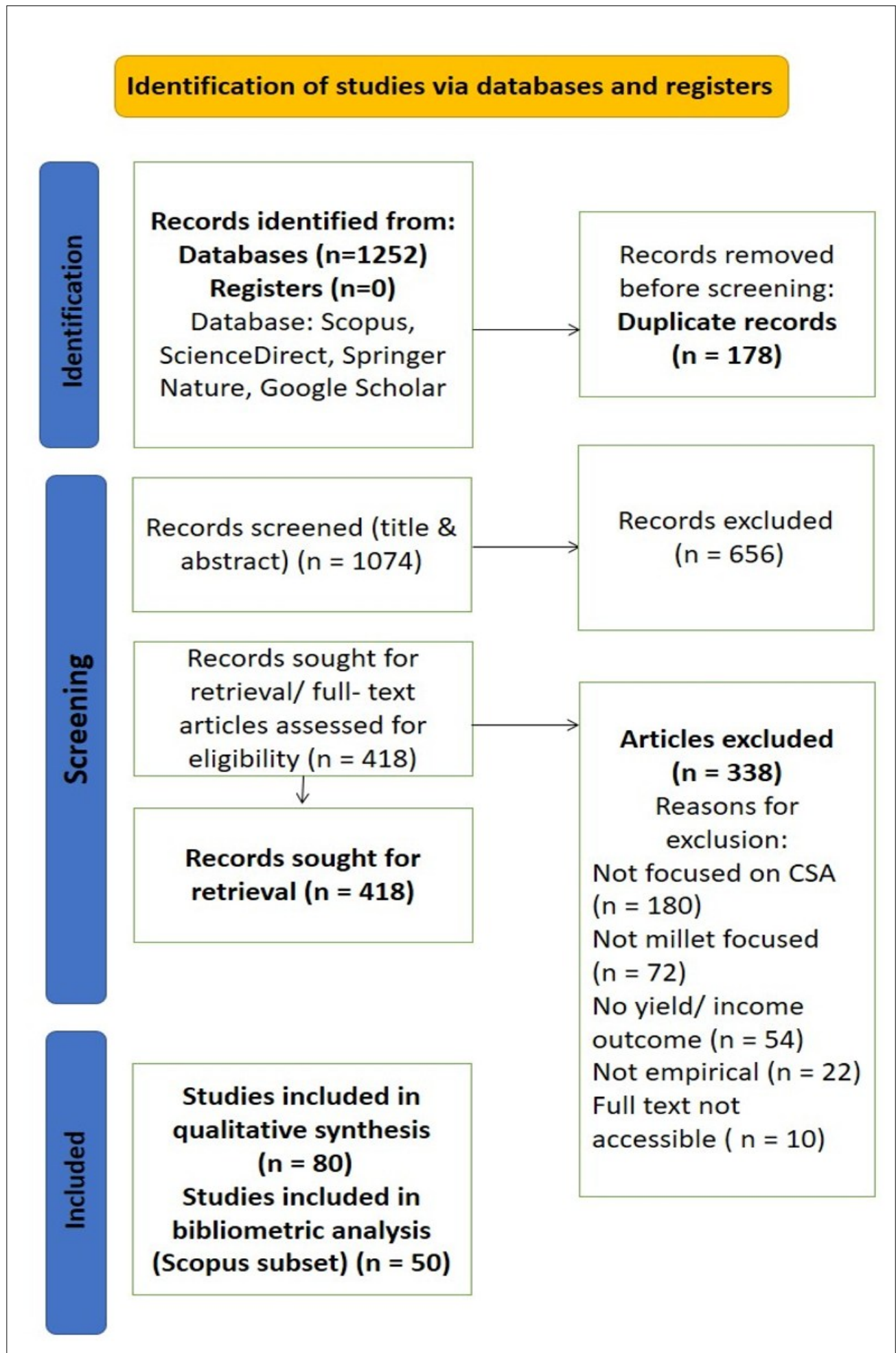


Fig. 1. Flowchart of article selection process using PRISMA protocol.

50 Scopus-indexed studies was used for bibliometric analysis. Of the 80 studies included in the final dataset, 58 are directly cited in the manuscript to support key arguments, while the remaining studies are incorporated within the broader synthesis.

To ensure consistency and minimise selection bias, two independent reviewers validated study inclusion, quality screening and thematic coding decisions. Disagreements were resolved through discussion and consensus.

Data extraction and coding

A structured data extraction framework comprising 33 variables was developed to systematically capture bibliographic information, agro-ecological context, millet species, CSA practices, outcome indicators, analytical methods and key findings for each study. Additional variables were incorporated to align with the TCCM framework, enabling classification of studies across TCCM dimensions.

The Scopus-indexed subset ($n = 50$) was separately coded for bibliometric variables, including author affiliations, keyword frequency, citation patterns and collaboration networks. Extracted data were cross-verified for consistency and completeness prior to analysis. The complete coding structure and variable classification framework are presented in Supplementary Table 2.

Bibliometric and visual analysis

Bibliometric analysis was conducted on the Scopus-indexed subset ($n = 50$) to characterise research trends, thematic evolution and collaboration patterns in millet-based CSA research. Descriptive statistics were generated using Microsoft Excel, while VOS viewer software was used to construct co-authorship, keyword co-occurrence and country collaboration networks based on association-strength normalisation.

Temporal trends were analysed using R and alluvial diagrams were generated using Python-based visualisation tools to examine thematic transitions across CSA domains and TCCM dimensions. These analyses were used to complement the narrative synthesis by providing structural insights into the evolution of the research field.

Theory, context, characteristics and methodology framework application

To enable system-level analysis, the TCCM framework was applied to classify and interpret the included studies. The framework allows examination of how research is conceptually grounded (theory), where it is conducted (context), what types of interventions are studied (characteristics) and how evidence is generated (methodology).

The integration of TCCM within millet-based CSA systems is conceptualised as a coupled socio-ecological structure linking biophysical processes, farmer decision-making and institutional dynamics. The integrated TCCM-SMART analytical framework (Fig. 2) conceptually illustrates the interactions between biophysical processes, institutional structures and farmer decision-making in millet-based CSA systems and forms the analytical basis of this study.

SMART classification of climate smart agriculture practices

Climate smart agriculture (CSA) practices identified in the reviewed studies were classified using a SMART functional framework, which categorises interventions based on their roles in productivity, adaptation and mitigation. Practices were grouped into domains such as water-smart, nutrient-smart, carbon-smart, weather-smart, genetic-smart, knowledge-smart and system-smart interventions.

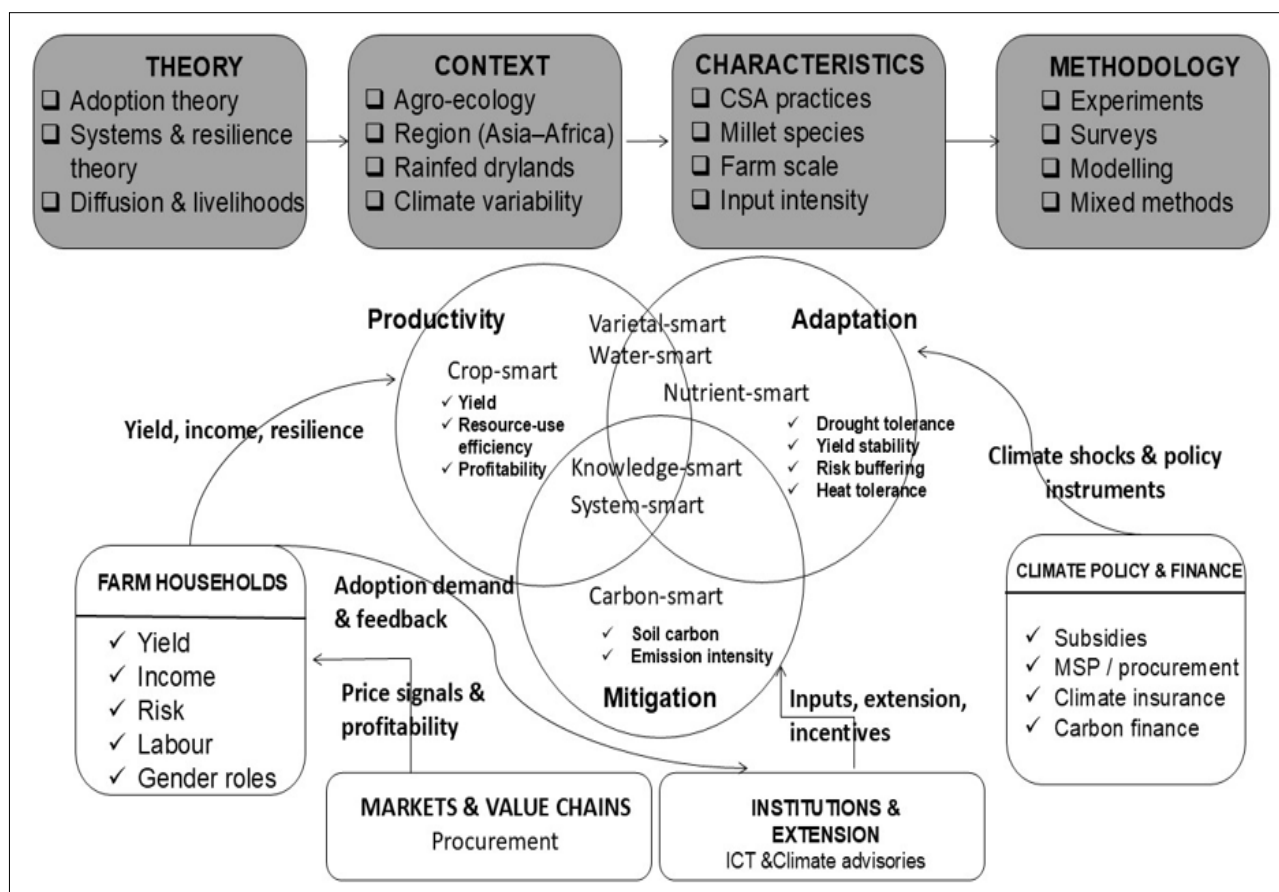


Fig. 2. Integrated theory, context, characteristics and methodology (TCCM) -SMART analytical framework for millet-based climate-smart agricultural systems.

This classification enabled cross-comparison of CSA practices across functional roles and facilitated mapping of interactions between agronomic performance, resilience outcomes and environmental impacts.

Synthesis approach and analytical limitations

Given the substantial heterogeneity in agro-ecological conditions, experimental designs, outcome indicators and reporting formats across studies, a narrative–thematic synthesis approach was adopted. Evidence was synthesised through thematic grouping of CSA practices, semi-quantitative comparison of reported yield and income responses and cross-context interpretation of resilience and environmental outcomes.

A formal meta-analysis was not conducted due to inconsistent reporting of variance measures, lack of standardised experimental designs and limited comparability of effect sizes across studies. Conducting statistical pooling under such conditions would risk creating a false sense of precision and violate assumptions required for quantitative synthesis.

Instead, reported outcome ranges are presented as indicative performance patterns derived from individual studies and should not be interpreted as statistically pooled or meta-analytical estimates. Variability in reported outcomes reflects differences in agro-ecological conditions, management practices and study contexts.

This approach enables integration of agronomic, socio-economic, institutional and modelling evidence within a unified analytical framework while maintaining methodological transparency. This approach aligns with best-practice guidance for synthesis under high heterogeneity, prioritising interpretive validity over statistical aggregation.

Quality assessment and risk-of-bias considerations

Given the heterogeneity of study designs included in this review, a formal quantitative risk-of-bias scoring tool was not applied. Instead, study quality was assessed using predefined screening criteria related to methodological clarity, relevance to CSA in millet systems, transparency of outcome reporting and adequacy of empirical evidence. Studies lacking clear methodological

description, outcome indicators or millet-specific relevance were excluded during full-text screening. Additional consideration was given to sample adequacy, consistency of reported findings and appropriateness of analytical methods. This qualitative appraisal approach was adopted to ensure interpretive reliability while accommodating the diversity of agronomic, socio-economic and modelling studies included in the review.

Findings

Bibliometric landscape and thematic positioning of millet-climate smart agriculture research

To contextualise the system-level synthesis, a bibliometric assessment was conducted on a subset of 50 Scopus-indexed studies drawn from the final dataset of 80 articles. The analysis aims to characterise structural evolution, thematic orientation and collaboration patterns in millet-based CSA research, rather than to serve as a standalone bibliometric analysis.

Publication trends

The annual publication trend indicates a marked increase in millet-focused CSA research after 2020 (Fig. 3), reflecting growing global attention to climate resilience, dryland agriculture and nutrition-sensitive food systems. This acceleration corresponds with increased policy emphasis on CSA and the global recognition of millets as resilient crops, suggesting that recent growth in the literature is driven largely by institutional and policy priorities rather than purely academic expansion (2, 11–13). Fig. 3 illustrates this upward trend, highlighting a sharp increase in publications after 2020. The trend reflects growing global interest in climate-resilient agriculture, dryland systems and millet-based food security strategies.

International collaboration patterns

The international collaboration network reveals a strong concentration of research activity within the Global South. India emerges as a central node, exhibiting extensive collaboration with countries such as Ethiopia, Mali, the United States and Japan. West African countries including Mali, Niger and Ghana form a closely connected cluster, reflecting shared agro-ecological conditions and development priorities.

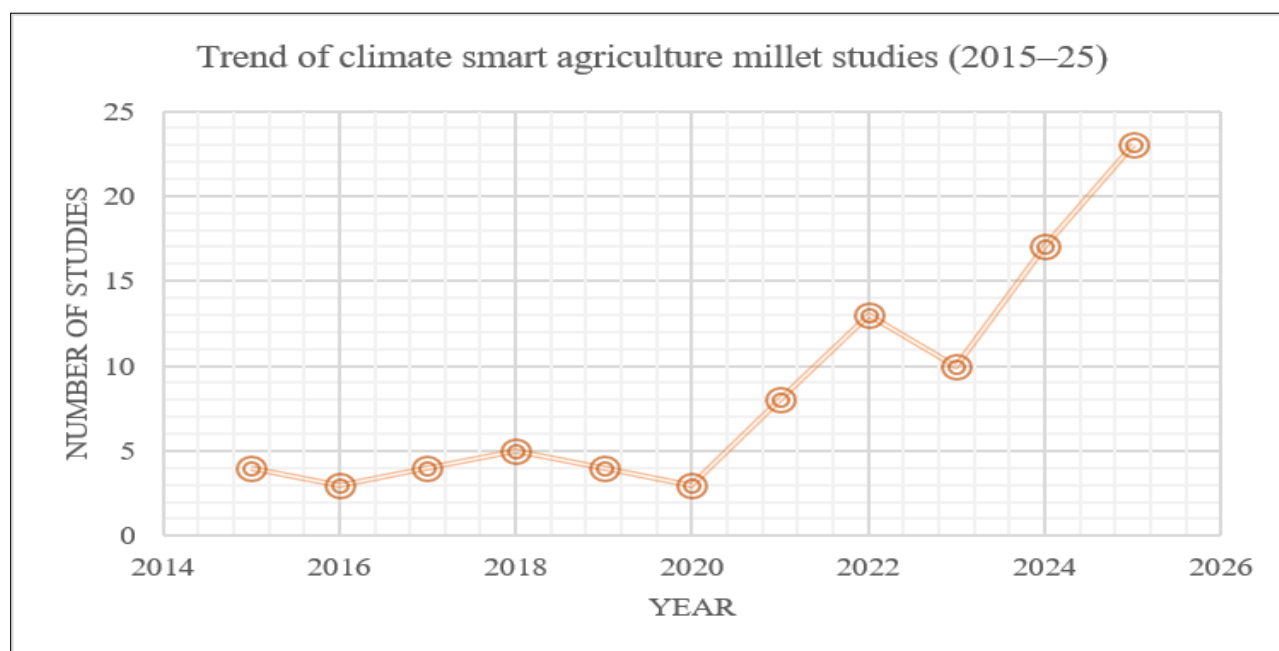


Fig. 3. Annual publication trend of millet-based climate-smart agriculture studies (2015–25).

In contrast, countries such as the United States and China contribute primarily through modelling, simulation and analytical research, while European countries demonstrate relatively limited but consistent collaborative engagement. This pattern indicates an asymmetric but complementary structure, where empirically rich dryland regions interact with methodologically specialised research systems and Fig. 4 highlights the central role of India and strong collaboration among African dryland regions. (Fig. 4).

Thematic orientation and keyword structure

The keyword co-occurrence network indicates that millet-based CSA research is strongly centred on drought stress, crop productivity and water-use efficiency. High-frequency keywords include “drought”, “yield”, “adaptation” and “pearl millet”, reflecting a dominant focus on agronomic performance under climate variability (Fig. 5).

Keywords related to food security and nutrition appear as secondary clusters, while mitigation-related and institutional keywords remain comparatively peripheral. Climate-system concepts such as “climate change” and “climate-smart agriculture” function as bridging nodes connecting multiple thematic clusters.

These patterns indicate that the current evidence base is heavily oriented toward productivity and adaptation outcomes, with relatively limited integration of mitigation and institutional dimensions.

Temporal shift toward integrated climate smart agriculture approaches

A temporal interpretation of thematic patterns indicates a gradual transition from single-practice interventions toward integrated CSA approaches. Early studies (2015–18) predominantly focused on individual technologies such as stress-tolerant varieties, soil moisture conservation and nutrient management. In contrast, post-2020 studies increasingly evaluate bundled interventions that combine varietal improvement, nutrient optimisation and water management.

This shift reflects growing recognition that CSA outcomes in millet systems are shaped by interactions among multiple practices rather than isolated interventions. However, empirical integration of institutional coordination, policy alignment and scaling mechanisms remains limited due to the lack of multi-scale, longitudinal and cross-institutional studies, indicating a persistent gap in system-level understanding.

Climate smart agriculture pillar and thematic distribution in millet systems

Distribution of studies across climate smart agriculture pillars

The distribution of studies across CSA pillars indicates a clear dominance of productivity-adaptation combinations, reflecting the empirical prioritisation of short-term risk buffering and yield stabilisation in millet-based systems. Relatively fewer studies explicitly address mitigation outcomes, which remain weakly quantified and often indirectly inferred through soil carbon or emission-intensity indicators (21, 34).

Fig. 6 illustrates the relative frequency of studies addressing different CSA pillar combinations. Productivity adaptation dominates the evidence base, while mitigation-focused studies remain limited.

Thematic distribution of climate smart agriculture practices across pillars

Millet-based CSA research is strongly concentrated around agronomic interventions aimed at improving yield and drought resilience. Soil-water conservation, nutrient management and varietal improvement form the core of productivity-oriented strategies, while diversification and agroforestry contribute to adaptation and mitigation linkages.

The heatmap illustrates the concentration of CSA practices across productivity, adaptation and mitigation domains, highlighting the dominance of agronomic interventions and the relatively limited representation of mitigation-oriented practices (Fig. 7). Table 2 summarises key CSA mechanisms, indicators and representative practices identified in the reviewed studies. Practices are categorised based on their dominant functional roles within CSA pillars, supported by representative empirical evidence.

Outcome patterns and indicative performance ranges

Yield and resource-use responses to CSA practices in millet systems show substantial variability across studies, reflecting differences in agro-ecological conditions, management practices and experimental designs. Soil-water conservation, nutrient optimisation and improved varieties consistently demonstrate the most robust and widely reported productivity gains, while diversification and integrated CSA bundles contribute to system resilience and income stability.

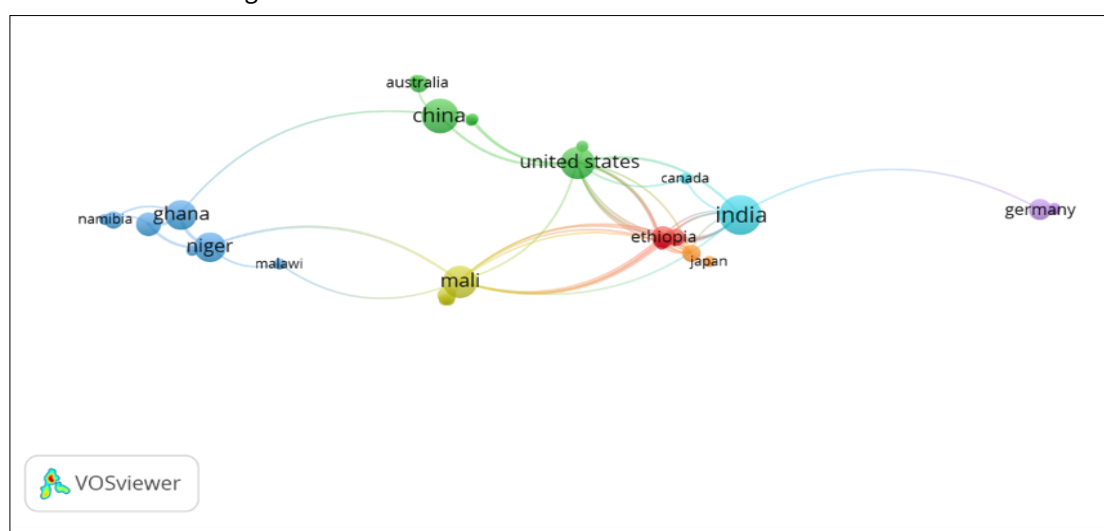


Fig. 4. International collaboration network of millet-based climate-smart agriculture research.

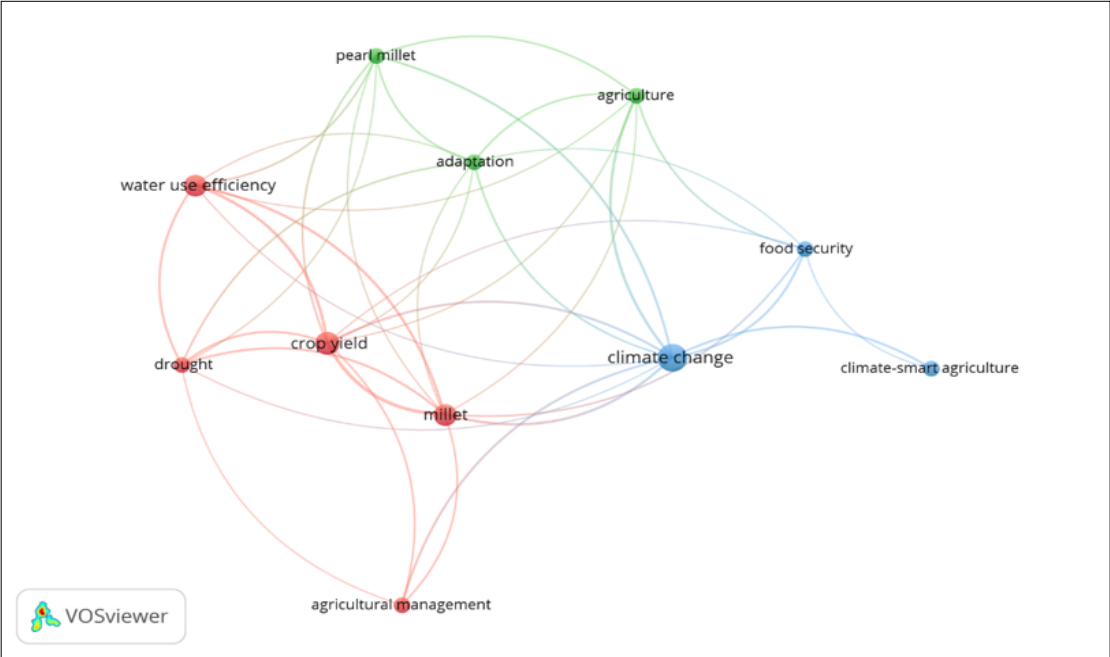


Fig. 5. Keyword co-occurrence network of millet-based climate-smart agriculture research.

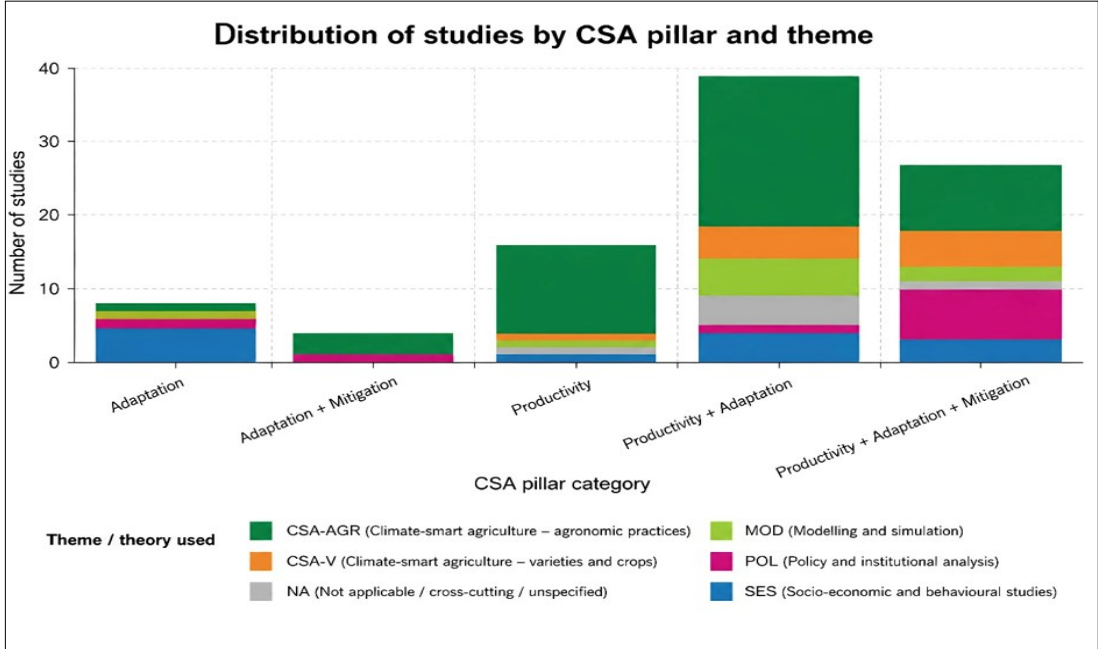


Fig. 6. Distribution of millet-based climate smart agriculture studies across productivity, adaptation and mitigation pillars.

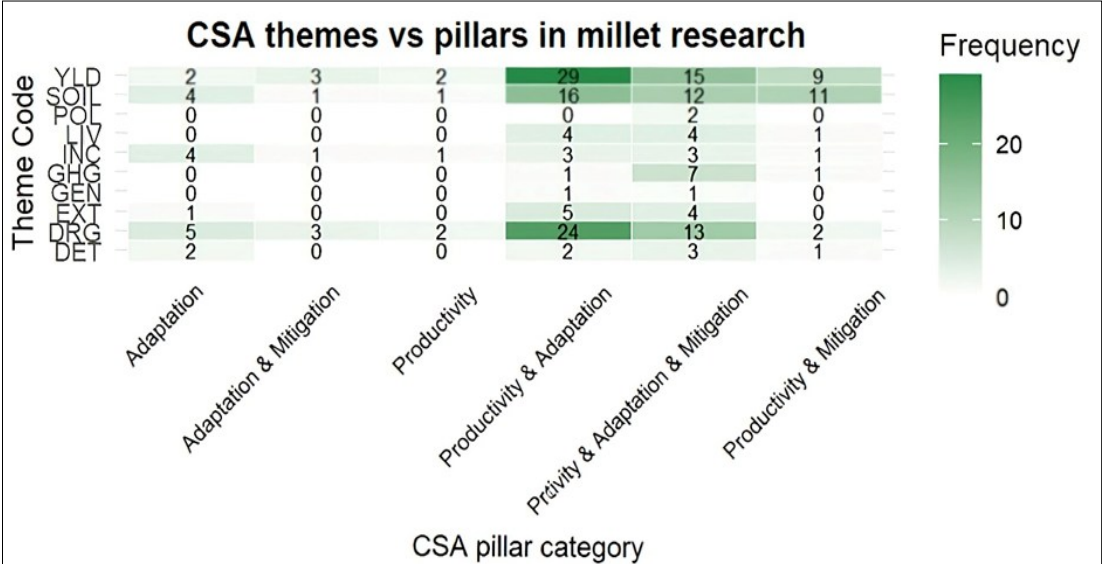


Fig. 7. Thematic distribution of climate smart agriculture (CSA) practices across CSA pillars in millet-based systems.

Table 2. Classification of millet-based climate-smart agriculture practices across productivity, adaptation and mitigation pillars

CSA pillar	Core mechanisms	Typical indicators used in studies	Representative practices	Key supporting references
Adaptation	Soil-water conservation, risk buffering, improved microclimate, phenological adjustment, integration of local/indigenous knowledge (ITK).	Water-use efficiency (WUE); yield stability (CV); seedling establishment; survival rate; adaptation index; sowing/planting date response.	Zai pits; contour/tied bunds; rainwater harvesting; transplanting; staggered planting; FMNR; drought-tolerant / early-maturing varieties; mulching.	(14, 16)
Productivity	Resource-use efficiency (nutrient, water, light); agronomic intensification; optimised nutrient regimes; improved varietal performance.	Grain yield; NUE; biomass; harvest index; gross margin; cost-benefit ratio (B:C).	Micro-dosing; split N; INM (FYM + RDF); high-density sowing; SRI/SCI; seed priming; improved millet varieties; integrated nutrient management.	(1, 16, 17)
Mitigation	Carbon sequestration, residue retention, reduced N losses, improved soil organic carbon, reduced emission intensity.	Soil carbon stocks; N ₂ O/CH ₄ /CO ₂ fluxes; GWP; emission intensity (kg CO ₂ -eq per unit yield).	Agroforestry (Faidherbia albida); biochar; residue retention; reduced tillage; neem-coated urea; organic amendments.	(16, 34)

FMNR: farmer-managed natural regeneration; NUE: nutrient use efficiency; N: nitrogen; INM: integrated nutrient management; FYM: farmyard manure; RDF: recommended dose of fertilisers; SRI: system of rice intensification; SCI: system of crop intensification; N₂O: nitrous oxide; CH₄: methane; CO₂: carbon dioxide; GWP: global warming potential.

Reported ranges represent synthesised central tendencies from individual studies and are presented for comparative interpretation only. Due to heterogeneity in study design, agro-ecological conditions and absence of consistent variance reporting, these values should not be interpreted as pooled or meta-analytical estimates.

Although Table 3 provides indicative performance ranges across CSA practices, outcome variability is strongly influenced by contextual factors such as soil type, rainfall variability, agro-ecological conditions and regional management practices. Due to inconsistent reporting across studies, stratified comparison based on these contextual variables was not uniformly feasible within the present synthesis.

Mechanistic pathways across climate smart agriculture pillars

Mechanistic linkages across CSA pillars indicate that adaptation outcomes are primarily driven by soil-water conservation practices such as mulching, contour bunding and rainwater harvesting, along with microclimate regulation and phenological adjustment. Productivity gains are associated with improved resource-use efficiency, nutrient optimisation and varietal performance, while mitigation effects are largely indirect and

remain under-represented in empirical studies. These pathways highlight the interdependence of CSA pillars, where productivity and adaptation outcomes are strongly coupled, while mitigation remains weakly integrated within millet-based systems. For example, water-smart interventions such as mulching, contour bunding and ridge-furrow systems improve infiltration, reduce evapotranspiration losses and enhance soil-moisture retention, thereby contributing to both adaptation and productivity outcomes. Similarly, nutrient-smart practices improve nutrient-use efficiency and biomass accumulation, while stress-tolerant varieties stabilise yield under rainfall variability. However, quantitative linkage analysis across CSA pillars remains limited due to inconsistent reporting of process-level indicators and lack of standardised measurements across studies.

SMART-climate smart agriculture functional alignment

The SMART classification reveals that water-smart and nutrient-smart practices dominate the millet-CSA evidence base, consistent with the strong emphasis on productivity and adaptation outcomes. Carbon-smart and energy-smart practices are comparatively less represented, while knowledge- and system-smart interventions are often assessed using qualitative or semi-quantitative indicators.

Table 3. Outcome patterns and indicative performance ranges of climate smart agriculture practices in millet-based systems

CSA theme	Dominant pillar(s)	Yield / Outcome effect (Range; n studies)	Key references
Soil-water conservation practices	Productivity; adaptation	Yield +8–70 % (n = 15); RWUE +24–55 % (n = 9); soil moisture +27–37 % (n = 6)	(22, 23, 34)
Nutrient optimisation (INM, microdosing, organics, nano-inputs)	Productivity; mitigation	Yield +20–108 % (n = 18); NUE +17–33 % (n = 7)	(22, 23, 34)
Crop diversification and intercropping	Productivity; adaptation	LER 1.27–1.65 (n = 9); Yield +27–38 % (n = 6)	(25, 26)
Improved varieties and stress-tolerant genotypes	Productivity; adaptation	Yield +25.8–112 % (n = 14); Income +26–30.3 % (n = 4); yield CV ≤ 9.4 % (n = 5)	(4, 20, 21, 31)
Mulching and ridge-Furrow Systems	Productivity; adaptation	Yield +27–42.8 % (n = 8); WUE +24–27.3 % (n = 5)	(23, 34)
Climate-smart intensification (SCI/ SRI analogues)	Productivity; adaptation; mitigation	Yield +20–100 % (n = 7); WUE +20–70 % (n = 6); seed saving up to 80 % (n = 3)	(1, 11, 14, 29)
Biofertilizers and microbial inoculants	Productivity; mitigation	Yield +16–65.4 % (n = 10); quality traits +16–20 % (n = 4)	(21, 23)
Modelling, forecasting and geospatial targeting	Productivity; adaptation	Yield deviation reduced 15–35 % (n = 9); model accuracy R ² = 0.85–0.97 (n = 6)	(18, 27, 28)
Integrated CSA bundles	Productivity; adaptation; mitigation	Yield +24–200 % (n = 11); Income +10–26 % (n = 6)	(14, 22, 29, 30)

CSA: climate smart agriculture; RWUE: rainwater use efficiency; INM: integrated nutrient management; NUE: nutrient use efficiency; LER: land equivalent ratio; CV: coefficient of variation; WUE: water use efficiency; SRI: system of rice intensification; SCI: system of crop intensification.

Table 4 categorises CSA practices into functional domains based on their roles in enhancing productivity, adaptation and mitigation. Representative practices and supporting studies are presented to illustrate functional alignment within millet agro-ecosystems. The distribution of evidence across SMART categories and research domains is further detailed in Supplementary Table 3.

System-level implications of pillar theme patterns

The combined analysis of CSA pillars and thematic distributions indicates a strong concentration of evidence in agronomic and varietal domains, while institutional, policy and mitigation dimensions remain comparatively underdeveloped. High-impact agronomic practices are well documented, but system-level integration involving governance, scaling mechanisms and value-chain development remains limited.

The evidence base remains strongly concentrated in agronomic and productivity-oriented domains, while institutional, policy and mitigation dimensions remain comparatively underrepresented. This imbalance highlights the need for more integrated system-level research linking technological, socio-economic and institutional dimensions of millet-based CSA systems. (9, 18, 31, 32). Addressing these constraints is critical for scaling CSA and achieving system-level transformation in millet-based agro-ecosystems.

Theory, context, characteristics and methodology mapping of millet-climate smart agriculture research

The TCCM framework was applied to examine how millet-based CSA research is conceptually framed, geographically distributed, operationalised through specific interventions and methodologically executed (33). This analysis provides a system-level understanding of how knowledge on CSA in millet systems is generated and where critical gaps persist.

Theory orientation of millet-climate smart agriculture studies

The theory dimension reveals that millet-CSA research is predominantly empirical and practice-driven, with limited explicit

engagement with formal theoretical frameworks. Most agronomic and varietal studies adopt implicit production-function or treatment-response approaches without referencing behavioural, systems or adoption theories (22–24). This pattern is particularly evident in studies focusing on nutrient management, conservation agriculture and varietal performance, where outcomes are evaluated primarily in terms of yield and resource-use efficiency (34–37).

A limited subset of studies explicitly incorporates theoretical frameworks such as the diffusion of innovation (DOI), sustainable livelihood framework (SLF) or innovation systems approaches to analyse adoption behaviour and institutional dynamics (9, 18). These studies highlight the importance of knowledge dissemination, institutional access and socio-economic conditions in shaping CSA uptake, but remain underrepresented within the broader evidence base.

In contrast, modelling-based studies rely on process-oriented theoretical structures embedded in crop simulation models such as DSSAT and AquaCrop, which provide strong biophysical representation but are rarely integrated with behavioural or institutional theory (26, 28, 38). This disconnect indicates that while the biophysical understanding of CSA interventions is relatively advanced, theoretical integration across socio-economic and institutional domains remains limited.

Contextual and agro-ecological distribution of millet-climate smart agriculture research

The contextual dimension shows a strong geographical concentration of millet-CSA research in Sub-Saharan Africa and South Asia, which together account for the majority of empirical studies (11, 18, 29, 31). Within Africa, research is heavily focused on Sahelian and Sudano-Sahelian regions, where pearl millet dominates under rainfed conditions characterised by low and variable rainfall (32, 39, 40). In South Asia, particularly India, studies are concentrated in semi-arid and dry sub-humid zones where finger millet and pearl millet are cultivated within mixed farming systems (3, 10, 39).

Table 4. SMART classification of climate-smart agriculture practices in millet-based systems

SMART criterion	Representative practices (Millet-based evidence)	Description	Key supporting references
Water-SMART	Tied-ridge/contour furrows; infiltration pits; plastic/straw mulching; rainwater harvesting; ridge-furrow planting; micro/supplemental irrigation.	Improves soil-moisture retention and WUE, reducing millet drought-period stress.	(22, 23)
Nutrient-SMART	FYM, vermicompost, integrated nutrient management; NPK microdosing; AMF/PSB inoculants; split-N; humic acid; INM packages.	Enhances millet nutrient-use efficiency and stabilises yields under nutrient stress.	(21–23)
Carbon-SMART	No-till and residue retention; agroforestry; compost; organic amendments; diversified rotations.	Builds soil carbon and lowers emission intensity in millet agroecosystems.	(10, 34)
Weather-SMART	Optimised sowing windows; transplanting; high-density planting; early/late maturing or drought-tolerant varieties.	Aligns millet phenology with rainfall patterns, reducing exposure to climate shocks.	(14, 20)
Seed/Genetic-SMART	Drought-tolerant lines; biofortified genotypes; QTL/GWAS-derived traits; stress-screened cultivars; AMF-enhanced rooting.	Strengthens genetic resilience and yield stability across variable climates.	(4, 19, 20, 27–28)
Energy-SMART	Reduced/conservation tillage; draught-animal traction; low-input agronomy; NPK microdosing.	Lowers labour and fuel requirements while maintaining millet productivity.	(21–22, 30)
Knowledge-/Information-SMART	Farmer training; participatory trials; indigenous knowledge; climate calendars; extension prioritisation.	Enhances adaptive capacity via farmer-led learning and climate information access.	(9, 17, 31, 34)
System-SMART	Intercropping (millet-legume); diversification; integrated crop-livestock; SCI; CSA bundles.	Improves system resilience and resource efficiency in millet-based farming.	(1, 8, 14, 24, 25, 29)

WUE: water use efficiency; FYM: farmyard manure; NPK: nitrogen, phosphorus and potassium; AMF: arbuscular mycorrhizal fungi; PSB: phosphate-solubilising bacteria; INM: integrated nutrient management; QTL: quantitative trait loci; GWAS: soil and water assessment system; SCI: system of crop intensification; CSA: climate-smart agriculture.

Across these regions, millet-based CSA research is closely aligned with smallholder production systems, where resource constraints, climate variability and livelihood vulnerability intersect. However, cross-regional comparative studies remain limited and there is relatively weak representation of millet systems in other dryland regions such as Latin America or parts of East Asia (2, 8).

Agro-ecological variability plays a critical role in shaping CSA outcomes. Differences in rainfall regimes, soil types and farming systems influence the performance of interventions such as microdosing, conservation agriculture and varietal selection, reinforcing the context-specific nature of CSA effectiveness (22, 23, 41).

Characteristics: typology of climate smart agriculture interventions

The characteristics dimension highlights the dominance of agronomic and varietal interventions within millet-CSA research. Soil-water conservation practices, nutrient optimisation strategies, stress-tolerant varieties and crop diversification represent the most frequently studied CSA interventions (16, 22–24, 26). These practices are primarily associated with productivity and adaptation objectives, reflecting the immediate priorities of smallholder farming systems under climatic stress.

Low-cost and scalable interventions such as seed priming, fertiliser microdosing and intercropping are particularly prominent, as they align with resource constraints and risk-management strategies of smallholder farmers (22, 24, 25). Integrated CSA bundles combining multiple practices are increasingly recognised as more effective than standalone interventions, as they address multiple constraints simultaneously (14, 32) (Fig. 8).

However, mitigation-oriented practices, including carbon sequestration, emission reduction and energy-use efficiency, remain underrepresented. Where mitigation is considered, it is often indirectly assessed through soil carbon or inferred emission intensity rather than direct measurement of greenhouse gas fluxes (34, 42, 43).

Methodological approaches and analytical trends

The methodological dimension indicates that millet CSA research is dominated by field experiments, on-farm trials and survey-based studies, supplemented by modelling and simulation approaches (9, 13, 18, 31). Field-based studies provide robust evidence on agronomic performance and resource-use efficiency, while survey-based studies contribute insights into adoption behaviour, socio-economic drivers and institutional constraints (9, 18, 31).

Modelling approaches, including DSSAT, AquaCrop and hydrological models, are increasingly used to simulate crop performance under varying climatic and management scenarios (26, 28, 38) (Fig. 9). While these tools enhance predictive capacity and support scenario-based analysis, they are often limited by parameter availability and lack of integration with socio-economic variables.

A key limitation across the literature is the lack of methodological integration. Few studies combine biophysical experimentation, socio-economic analysis and modelling within a unified framework, resulting in fragmented evidence that limits system-level interpretation (14). Additionally, inconsistencies in outcome measurement, lack of standardised indicators and limited reporting of variance measures constrain comparability across studies.

Synthesis: system-level gaps identified through theory-context-characteristics-methodology

The combined TCCM analysis reveals several critical gaps in millet-based CSA research. First, there is a clear imbalance between strong empirical evidence on agronomic performance and limited theoretical integration of socio-economic and institutional dynamics. Second, research remains geographically concentrated, with limited cross-regional comparative analysis. Third, CSA interventions are predominantly evaluated as isolated practices rather than components of integrated systems. Finally, methodological fragmentation limits the ability to generate comprehensive system-level insights. These findings indicate that millet-based CSA research remains fragmented across agronomic, socio-economic and institutional dimensions. Greater integration of theoretical, contextual and methodological approaches is needed to support system-level understanding of climate-resilient millet agro-ecosystems (16, 31).

The CSA technologies operate as niche innovations influencing farm household decision-making through productivity, income and learning effects (Fig. 10). Reinforcing feedback loops (R1, R2) represent productivity income and learning diffusion dynamics that accelerate CSA adoption, whereas balancing feedback loops (B1–B4) represent constraints related to credit limitations, labour burden, gendered access to resources and market failure that inhibit adoption. Dotted callouts indicate key institutional leverage points.

Adoption dynamics, constraints and system-level interactions

While the TCCM analysis identified broader structural and methodological gaps in millet-based CSA research, this section specifically examines the socio-economic and institutional factors influencing adoption of CSA practices at the farm and system levels. Adoption of CSA practices in millet-based systems is shaped by a complex interaction of socio-economic, institutional and biophysical factors. Despite strong empirical evidence on the productivity and resilience benefits of CSA interventions, adoption rates remain uneven across regions and farming systems. This reflects the fact that adoption is not determined solely by technological performance but by access to resources, information, institutional support and market opportunities (9, 18, 31).

At the household level, factors such as education, farm size, income, risk perception and access to extension services significantly influence adoption decisions. Studies consistently show that farmers with better access to climate information, credit and extension support are more likely to adopt improved varieties, soil-water conservation practices and nutrient management strategies (3, 35). Conversely, labour constraints, limited financial capacity and inadequate input availability act as major barriers, particularly for resource-poor smallholders operating under rainfed conditions (9, 44).

Institutional factors play a critical role in shaping adoption outcomes. Weak extension systems, fragmented policy implementation and limited coordination among stakeholders constrain the dissemination and scaling of CSA practices. In many cases, the absence of effective institutional linkages between research, extension and market systems limits the translation of technological innovations into field-level adoption (18, 45). Furthermore, policy support for millets has historically

TCCM flow (theme → region → methodology) across CSA pillars Simplified to Productivity, Adaptation, and Mitigation

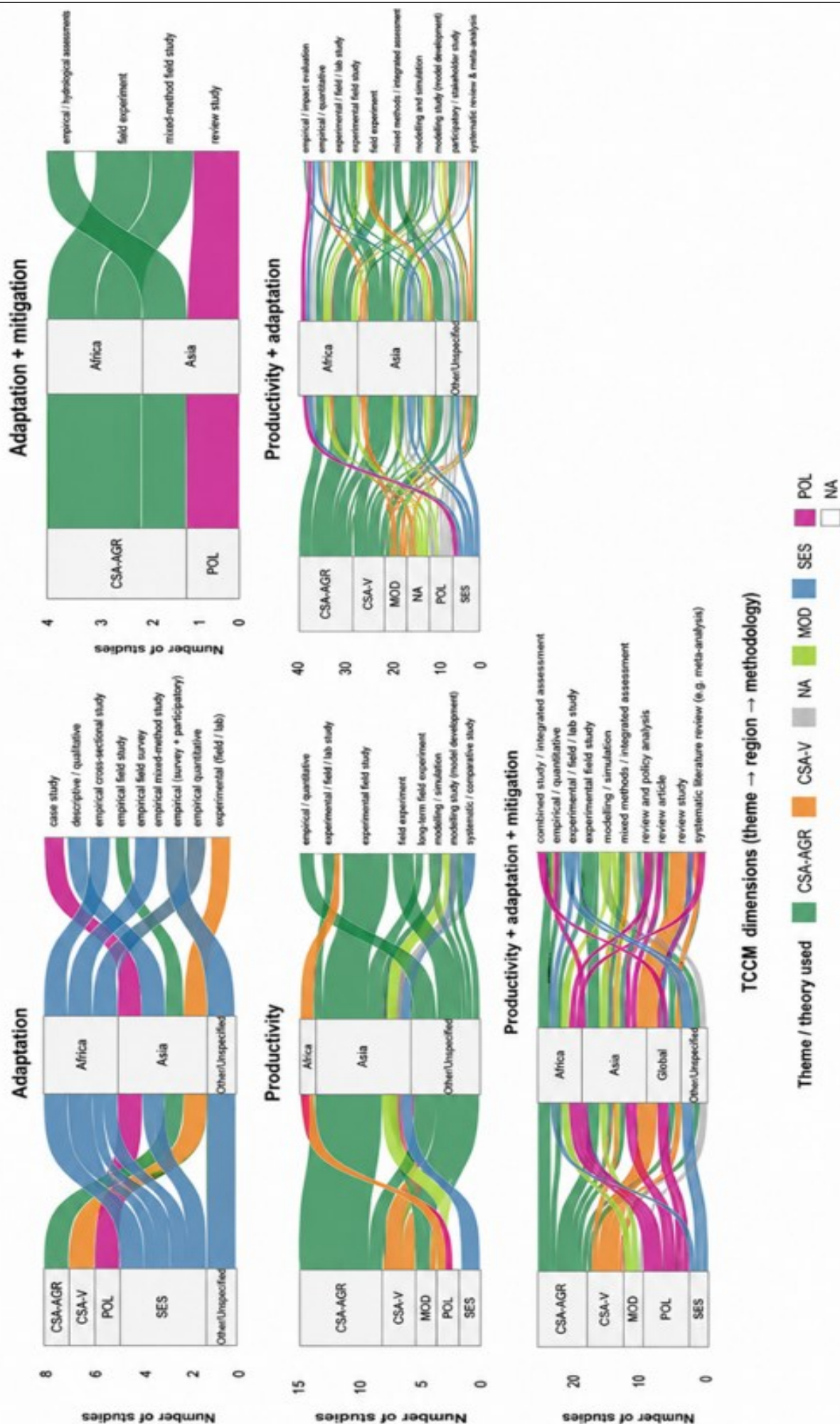


Fig. 8. Alluvial representation of theory-context-characteristics-methodology (TCCM) dimensions across themes, regions and methodologies.

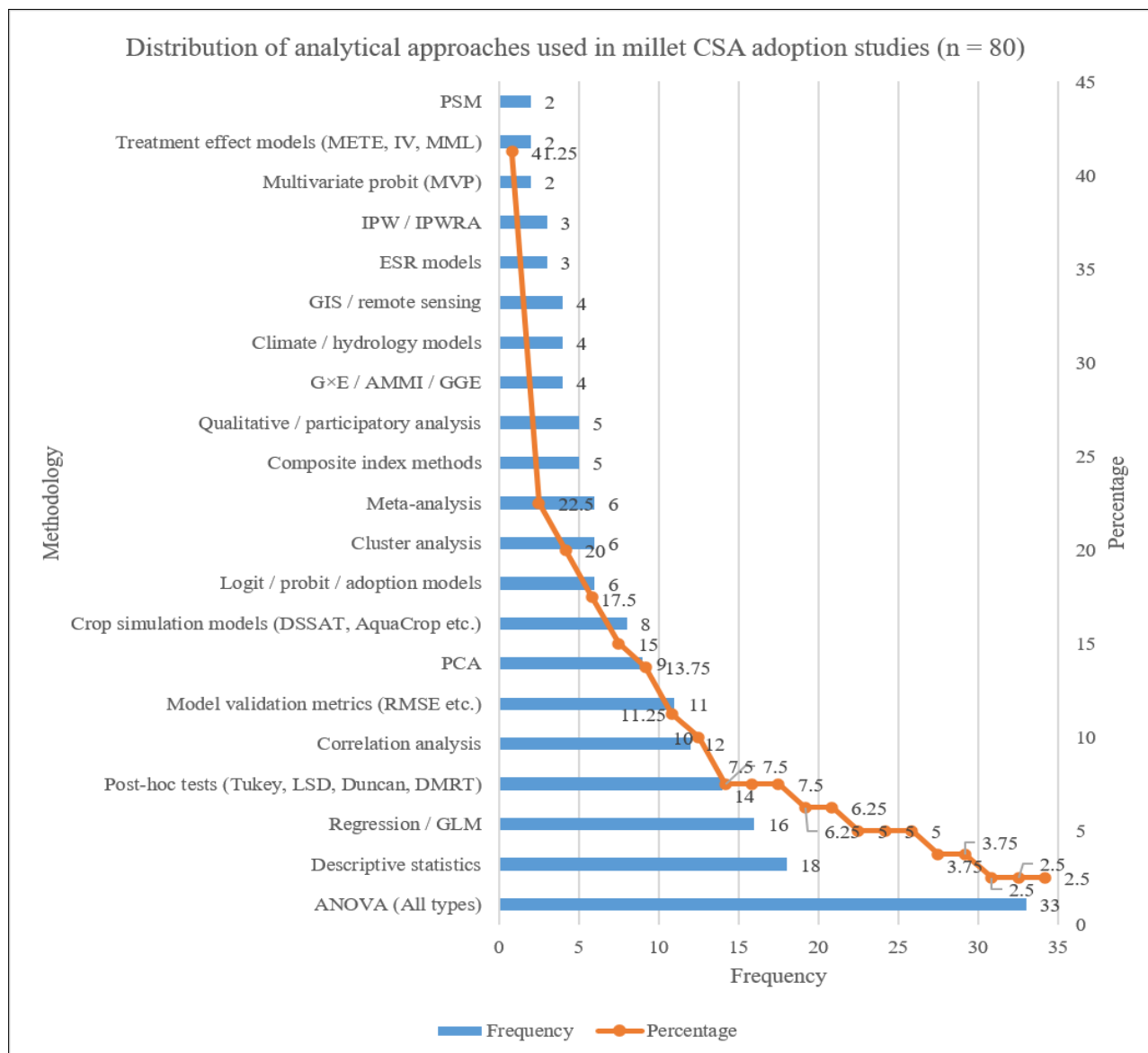


Fig. 9. Distribution of analytical methods across the millet-based climate smart agriculture (CSA) studies.

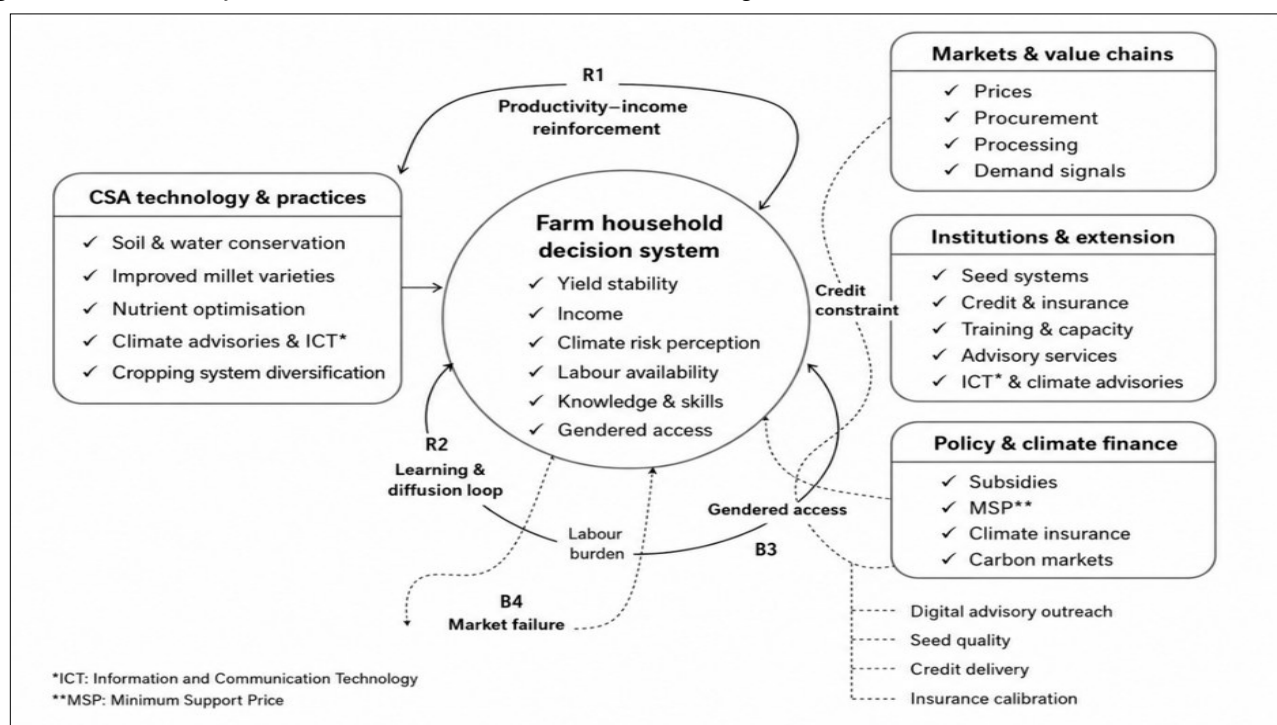


Fig. 10. Climate smart agriculture (CSA) adoption in millet systems as a socio-technical transition shaped by reinforcing and constraining feedback loops.

been inconsistent, contributing to underdeveloped value chains and limited incentives for farmers to invest in improved practices (11, 12).

Market access and value-chain development are equally important determinants of adoption. While CSA interventions may improve productivity and resilience, their economic viability depends on access to stable markets, price incentives and processing infrastructure. Studies indicate that weak market integration and limited value addition reduce the profitability of millet-based systems, thereby discouraging adoption of improved technologies (10, 11). In contrast, regions with better market linkages and institutional support show higher adoption rates and more sustained transitions toward climate-resilient practices (6, 30).

Another important dimension is the role of knowledge systems and farmer perceptions. Adoption of CSA practices is influenced by farmers' understanding of climate risks, perceived benefits of technologies and compatibility with existing farming systems. Participatory approaches, local knowledge integration and farmer-to-farmer learning have been shown to enhance adoption by improving trust and reducing uncertainty associated with new practices (9, 17). However, such approaches remain underutilised in many millet-growing regions.

At the system level, adoption patterns reflect interactions between technological, institutional and market factors. The CSA practices that are low-cost, labour-efficient and compatible with existing farming systems such as seed priming, microdosing and intercropping tend to exhibit higher adoption potential (22, 24). In contrast, practices requiring higher initial investment or institutional support show slower uptake despite their potential benefits (14).

Overall (Fig. 11, Table 5), adoption of CSA practices in millet systems is shaped by the interaction of household resources, institutional support, market access and knowledge systems. These findings highlight the importance of coordinated extension, policy and value-chain interventions for improving the scalability and sustainability of climate-smart millet farming systems (16, 18).

Results and Discussion

The findings of this review indicate that CSA practices in millet-based systems are primarily effective in improving productivity and adaptation outcomes. Soil-water conservation, nutrient management and improved varieties consistently enhance yield stability and resource-use efficiency across diverse agro-ecological conditions. However, the effectiveness of these practices varies depending on local environmental conditions, management practices and access to institutional support. While agronomic benefits are well established, their translation into sustained farm-level outcomes depends on adoption, which is influenced by access to inputs, extension services and market opportunities.

Reframing climate smart agriculture in millet systems as a system level problem

The synthesis shows that CSA in millet-based systems has been predominantly approached as a set of discrete agronomic interventions rather than as an integrated socio-ecological system. While substantial evidence exists on yield enhancement, water-use efficiency and resilience benefits of individual practices, these gains do not consistently translate into sustained system-level outcomes. This gap arises because CSA performance in millet systems is shaped not only by biophysical responses but also by interactions among institutional arrangements, market structures and farmer decision-making processes (14, 16).

The dominance of productivity adaptation pathways identified in this review reflects the immediate priorities of smallholder farmers operating under climatic risk. However, the relatively weak integration of mitigation and institutional dimensions indicates that current CSA approaches remain incomplete. Similar imbalances have been noted in broader CSA assessments, where mitigation outcomes are often secondary and poorly quantified (34, 43). Addressing this imbalance requires moving beyond technology-centric approaches toward frameworks that explicitly incorporate governance, incentives and system coordination.

Table 5. Key constraints, underlying causes and intervention strategies in millet-based climate smart agriculture systems

Constraint	Underlying cause	Impact on CSA outcomes	Suggested intervention
Limited access to inputs (seeds, fertilisers)	Weak supply chains; high transaction costs	Low adoption of improved varieties and nutrient practices	Strengthen input delivery systems; promote local seed systems
Financial constraints and credit access	Lack of institutional credit; risk aversion	Reduced investment in CSA technologies	Expand credit schemes; climate risk insurance; subsidies for initial adoption
Labour constraints	High labour requirement of certain CSA practices	Low adoption despite productivity benefits	Promote labour-saving technologies; mechanisation support
Weak extension services	Low extension coverage; poor knowledge transfer	Limited awareness and incorrect implementation	Strengthen extension systems; digital advisory platforms
Market access limitations	Poor value chains; price volatility	Reduced profitability of millet-based systems	Develop value chains; improve storage, processing and market linkages
Policy and institutional fragmentation	Lack of coordination across sectors	Poor scaling and sustainability of CSA interventions	Integrate policies; strengthen institutional coordination
Knowledge and perception gaps	Limited climate awareness; uncertainty about benefits	Hesitation in adopting new practices	Promote participatory approaches; farmer-to-farmer learning
Agro-ecological variability	Heterogeneous soils and rainfall	Inconsistent performance of CSA practices	Develop location-specific recommendations; climate advisories
High initial costs for integrated practices	Investment barriers	Slow uptake of CSA bundles	Provide incentives; phased adoption strategies

CSA: climate smart agriculture.

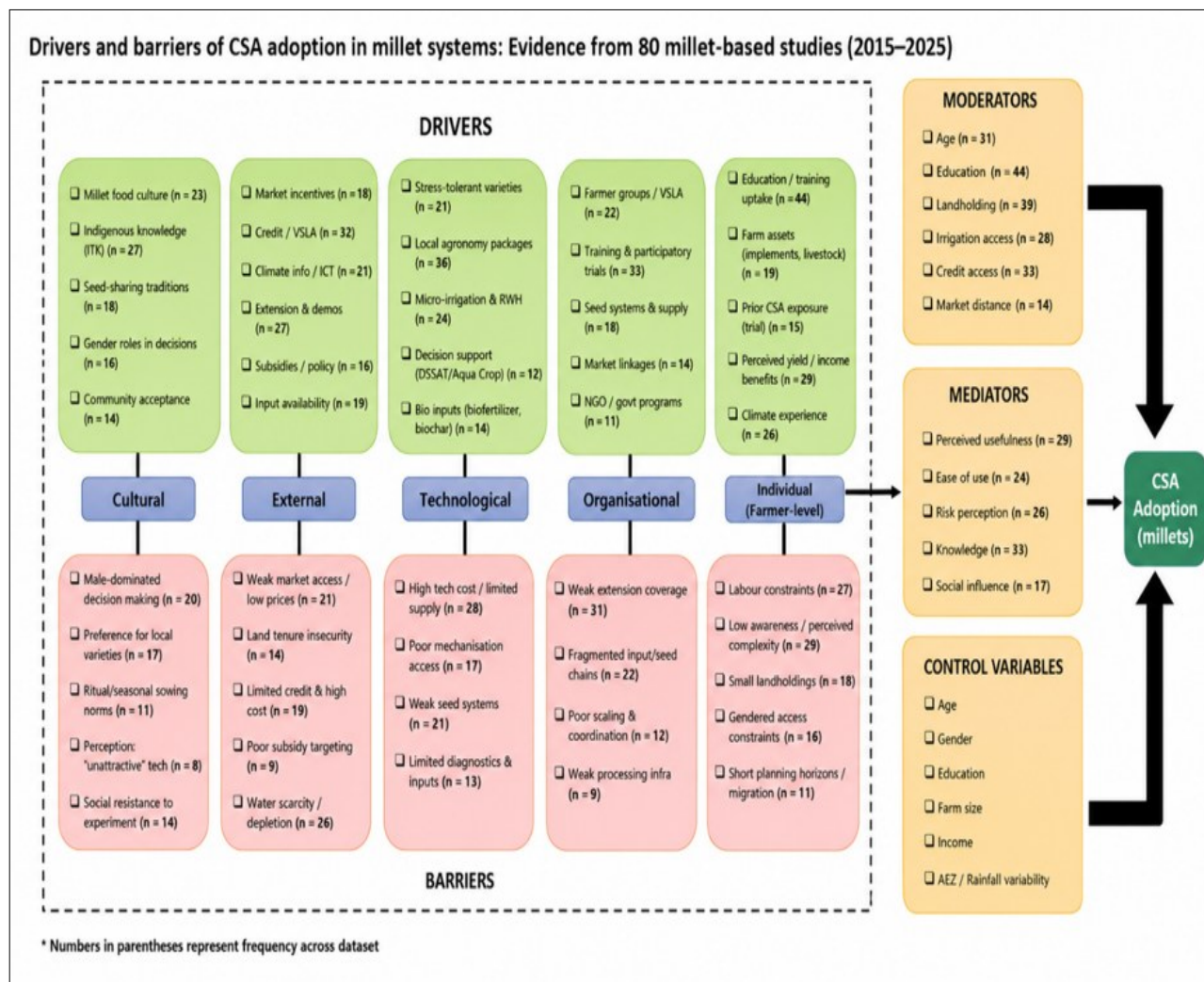


Fig. 11. Drivers and barriers of climate smart agriculture (CSA) adoption in millets.

Explaining the adoption impact gap

A central finding of this review is the persistent gap between demonstrated agronomic benefits and actual adoption of CSA practices. Although interventions such as microdosing, intercropping and stress-tolerant varieties show clear productivity gains, adoption remains uneven across regions. This divergence reflects structural constraints including limited access to inputs, weak extension systems and underdeveloped value chains (9, 18, 31).

Economic considerations further complicate adoption dynamics. In several cases, yield improvements are offset by increased labour requirements or input costs, reducing net returns and discouraging adoption by resource-constrained farmers (2, 30). These findings indicate that adoption decisions are influenced not only by productivity gains but also by labour requirements, input costs, perceived risks and institutional support. Consequently, CSA practices that are economically feasible, labour-efficient and compatible with existing farming systems are more likely to achieve sustained adoption (22, 24).

Role of institutions and value chains

The analysis highlights the central role of institutional systems in mediating CSA outcomes. Weak coordination among research, extension and market actors limits the diffusion and scaling of climate-smart practices. In millet systems, this challenge is compounded by historically limited policy support and fragmented value chains, which reduce incentives for farmers to adopt improved technologies (11, 12).

Strengthening institutional linkages is therefore critical for translating technological potential into real-world impact. Effective extension systems, access to climate information and integration with market opportunities can significantly enhance adoption and sustainability of CSA interventions (35, 45, 46). Moreover, value-chain development including processing, storage and market access plays a key role in improving profitability and reducing production risks.

Integrating biophysical and socio-economic evidence

One of the key limitations identified through the TCCM analysis is the lack of integration between biophysical and socio-economic research. Agronomic studies provide detailed insights into yield and resource-use responses, while socio-economic studies focus on adoption and livelihood outcomes. However, these domains are rarely combined within a unified analytical framework, resulting in fragmented understanding of system behaviour (47, 48).

Modelling approaches offer significant potential to bridge this gap by integrating climate, crop and management variables. However, current models remain largely biophysical and do not adequately incorporate socio-economic drivers of adoption and decision-making (26, 28, 49, 50). Developing integrated models that capture both biophysical processes and human behaviour is essential for improving the predictive capacity of CSA research and supporting evidence-based policy decisions.

Implications for system-level transition

The findings of this review suggest that achieving climate-resilient millet-based systems requires a transition from technology-

focused interventions to systems-oriented strategies. This involves aligning CSA practices with institutional frameworks, market systems and farmer realities. The combined TCCM-SMART approach proposed in this study provides a basis for such integration by linking technological characteristics with contextual and methodological dimensions.

From a policy perspective, interventions should prioritise:

- strengthening extension and advisory systems
- improving access to inputs and credit
- enhancing market linkages and value addition
- promoting integrated CSA bundles tailored to local conditions

Such measures can help overcome adoption barriers and enable scaling of climate-smart practices. Importantly, future research should focus on cross-regional comparative analysis, standardisation of outcome indicators and development of integrated assessment frameworks that capture interactions across CSA pillars. This transition requires coordinated alignment across technological innovation, institutional capacity and market integration, rather than isolated improvements in individual components.

Research gaps and future directions

This review identifies several areas for future research. First, there is a need for greater integration of theoretical frameworks, particularly those related to adoption behaviour and institutional dynamics. Second, mitigation outcomes require more rigorous quantification through direct measurement of greenhouse gas emissions and carbon dynamics. Third, cross-scale analyses linking farm-level practices with landscape and policy-level processes remain limited.

Additionally, improving data comparability across studies is essential for advancing synthesis research. Standardised reporting of yield, income and resilience indicators, along with consistent documentation of experimental conditions, would

enable more robust comparative analysis. Finally, greater emphasis on participatory and transdisciplinary approaches can enhance the relevance and applicability of CSA research in millet systems (Table 6).

Conclusion

This review shows that climate-smart agriculture (CSA) practices can substantially improve productivity, resilience and resource-use efficiency in millet-based farming systems, particularly through soil-water conservation, nutrient management, crop diversification and stress-tolerant varieties. The findings also indicate that integrated CSA approaches generally produce more stable and consistent outcomes than single interventions, highlighting the importance of adopting systems-oriented strategies in climate-resilient millet agriculture.

Despite these benefits, large-scale adoption of CSA practices remains constrained by weak institutional support, limited access to extension services, inadequate market linkages and financial barriers faced by smallholder farmers. Strengthening extension systems, improving access to quality inputs and credit, expanding climate advisory services and developing millet value chains are therefore essential for improving the long-term sustainability and scalability of CSA interventions.

The review further highlights important research gaps. Future studies should focus on long-term and multi-scale assessments that integrate agronomic, socio-economic and institutional dimensions within a common analytical framework. Greater attention is also needed for direct measurement of greenhouse gas emissions, development of standardised CSA indicators and region-specific evaluation of CSA performance under different rainfall regimes, soil conditions and farming contexts. In addition, combining crop modelling approaches with farmer adoption and institutional analysis could provide more realistic insights for policy and decision-making.

Table 6. Research gaps and future directions across theory-context-characteristics-methodology dimensions in millet-based climate smart agriculture research

TCCM dimension	Identified gap	Implication	Future research direction	Reference
Theory	Limited use of behavioural and institutional theories	Weak understanding of adoption dynamics	Integrate DOI, SLF and innovation systems frameworks	(9, 18, 35, 46, 51–53)
Context	Geographic concentration in Africa and South Asia	Limited global generalisability	Expand studies to other dryland regions	(28, 32, 54–56)
Characteristics	Focus on individual practices	Underestimation of system interactions	Evaluate integrated CSA bundles	(28, 57)
Methodology	Fragmented approaches (agronomic vs socio-economic)	Limited system-level insights	Combine experiments, surveys and modelling	(32, 40)
Mitigation dimension	Poor quantification of emissions and carbon dynamics	Incomplete CSA evaluation	Include direct GHG measurements and carbon accounting	(23, 47)
Adoption research	Limited longitudinal studies	Weak understanding of long-term adoption	Conduct panel and long-term studies	(21, 22, 43)
Indicators	Lack of standardised metrics	Poor comparability across studies	Develop standard CSA indicator frameworks	(9, 11)
Scaling pathways	Limited research on scaling mechanisms	Difficulty in large-scale implementation	Study policy, institutional and market pathways	(23, 24, 38)
Data integration	Weak linkage across datasets	Fragmented evidence base	Promote integrated data platforms	(41, 49, 52)

DOI: digital object identifier; SLF: sustainable livelihood framework; TCCM: theory, context, characteristics and methodology; CSA: climate smart agriculture; GHG: greenhouse gas.

Overall, achieving sustainable and climate-resilient millet-based systems will require coordinated efforts that link technological innovation with stronger institutions, better market systems and locally relevant policy support.

Acknowledgements

The authors acknowledge the academic and institutional support provided by Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India.

Authors' contributions

AMJ conducted the literature review, performed the analysis and drafted the manuscript. MAV, AJR, SK and RGS contributed to data curation, validation and critical revision of the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly for linguistic refinement, grammar correction and improvement of sentence clarity. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

- Adhikari PL, Ghimire B, Pariyar A, Ojha SK, Chapagain B, Maraseni R. System of crop intensification for more productive, resource-conserving, climate-resilient and sustainable agriculture. *Int J Agric Sustain*. 2018;16(1):1–28. <https://doi.org/10.1080/14735903.2017.1402504>
- Ahiamadia D, Ramilan T, Tozer PR. Enhancing climate resilience in northern Ghana: A stochastic dominance analysis of risk-efficient climate-smart technologies for smallholder farmers. *Environ Dev*. 2024;51:101031. <https://doi.org/10.1016/j.envdev.2024.101031>
- Autio A, Johansson T, Motaroki L, Minoia P, Pellikka P. Constraints for adopting climate-smart agricultural practices among smallholder farmers in Southeast Kenya. *Agric Syst*. 2021;194:103284. <https://doi.org/10.1016/j.agsy.2021.103284>
- Bandyopadhyay T, Muthamilarasan M, Prasad M. Millets for next generation climate-smart agriculture. *Front Plant Sci*. 2017;8:1266. <https://doi.org/10.3389/fpls.2017.01266>
- Beggi F, Vadez V, Buerkert A. Ammonium fertilization increases pearl millet yield by promoting early root growth, higher tillering and water use during grain filling in a low phosphorus Sahelian soil. *J Plant Nutr Soil Sci*. 2021;184(1):123–31. <https://doi.org/10.1002/jpln.202000347>
- Berhanu Y, Angassa A, Aune JB. System analysis of climate-smart agriculture technologies. *Agric Syst*. 2021;187:102988. <https://doi.org/10.1016/j.agsy.2020.102988>
- Bhatnagar S, Chaudhary R, Sharma S, Sharma S, Kumar R. Climate-smart agricultural practices for enhancing resilience and sustainability of farming systems under changing climate. *Environ Sustain Indic*. 2024;24:100535. <https://doi.org/10.1016/j.indic.2024.100535>
- Bitew Y, Alemayehu G, Adego E, Assefa A. Boosting land use efficiency, profitability and productivity of finger millet by intercropping with grain legumes. *Cogent Food Agric*. 2019;5(1):1702826. <https://doi.org/10.1080/23311932.2019.1702826>
- Chapke RR, Satyavathi CT, King EDO, Laxmiprasanna P, Priyanka V. Perceptions of climatic variability among millet farmers: Insights from tribal communities in the Kolli Hills, Tamil Nadu, South India. *Front Clim*. 2025;6:1332196. <https://doi.org/10.3389/fclim.2024.1506084>
- Clermont-Dauphin C, Ndiénor M, Leroux L, Ba HS, Bongers F, Jourdan C. *Faidherbia albida* trees form a natural buffer against millet water stress in agroforestry parklands in Senegal. *Biotechnol Agron Soc Environ*. 2023;27(3):20477. <https://doi.org/10.25518/1780-4507.20477>
- Coulibaly A, Traoré M, Sidibé D, Dakuo D, Bationo A, Zougmore R, et al. Sustainable intensification of sorghum and pearl millet production by seed priming, seed treatment and fertilizer microdosing under different rainfall regimes in Mali. *Agronomy*. 2019;9(10):664. <https://doi.org/10.3390/agronomy9100664>
- Food and Agriculture Organization of the United Nations (FAO). International Year of Millets 2023. Rome: FAO; 2024.
- Food and Agriculture Organization of the United Nations (FAO). Unleashing the potential of millets. Rome: FAO; 2023. <https://doi.org/10.4060/cc7484en>
- Fischer HW, Reddy NLN, Rao MLS. Can drought-resistant crops promote climate-secure agriculture? Millet cultivation in Anantapur. *World Dev Perspect*. 2016;2:5–10. <https://doi.org/10.1016/j.wdp.2016.06.005>
- World Bank. Climate-smart agriculture indicators. Washington (DC): World Bank; 2016.
- Khaya SA, Talukder SK, Datta P, Rahman MM, Islam MT, Hossain MA. Millets as climate-resilient crops for ensuring food and nutritional security under changing climate. *Heliyon*. 2023;9(11):e22123. <https://doi.org/10.1016/j.heliyon.2023.e22123>
- Grovermann C, Umesh KB, Quiédeville S, Krishna WV, Jose S, Birner R. Productivity and profitability of finger millet-based systems in smallholder agriculture. *Agriculture*. 2018;8(9):131. <https://doi.org/10.3390/agriculture8090131>
- Guo DX, Chen CF, Guo PY, Yuan XY, Xing XG, Ma XY. Evaluation of AquaCrop model for foxtail millet growth and water use. *Water*. 2018;10(7):836. <https://doi.org/10.3390/w10070836>
- Gupta SK, Sharma KK, Govindaraj M. Finger millet: A solution to food insecurity and hidden hunger under stressful environments. *Front Plant Sci*. 2017;8:643. <https://doi.org/10.3389/fpls.2017.00643>
- Harish MS, Bhuker A, Chauhan BS. Millet production challenges and climate resilience pathways. *Front Sustain Food Syst*. 2024;8:1386469. <https://doi.org/10.3389/fsufs.2024.1386469>
- Hatti V, Ramachandrapa BK, Sathish A, Thimmegowda MN. Soil properties and productivity of rainfed finger millet under conservation tillage and nutrient management. *J Environ Biol*. 2018;39(5):612–24. <https://doi.org/10.22438/jeb/39/5/MRN-724>
- Ibrahim A, Abaidoo RC, Fatondji D, Opoku A. Microdosing improves yield and water use efficiency in millet-based systems. *Field Crops Res*. 2015;180:29–36. <https://doi.org/10.1016/j.fcr.2015.04.022>
- Ibrahim A, Abaidoo RC, Fatondji D, Opoku A. Integrated use of fertilizer microdosing and mulching increases millet yield and water use efficiency in Sahelian environments. *Nutr Cycl Agroecosyst*. 2015;103(3):375–88. <https://doi.org/10.1007/s10705-015-9752-z>
- Kangah H, Boateng Agyenim J. Planned climate adaptation interventions and smallholder farmer output levels in Ghana. *Cogent Soc Sci*. 2022;8(1):2108214. <https://doi.org/10.1080/23311886.2022.2108214>
- Derebe B, Worku A, Chanie Y, Wolie A. On-farm participatory evaluation and selection of legumes intercropped with finger millet

- in Western Amhara. *Heliyon*. 2021;7(11):e08319. <https://doi.org/10.1016/j.heliyon.2021.e08319>
26. Kumar S, Kumar A, Sen H, Janeja HS, Maity S, Banerjee S, et al. Small millets: A multifunctional crop for sustainable food security under climate change. *Plant Sci Today*. 2024;11(4):1220–29. <https://doi.org/10.14719/pst.4113>
 27. Liu T, Yang X, Batchelor WD, Liu Z, Zhang Z, Wan N, et al. Climate-smart modelling of foxtail millet under future climate scenarios. *Agric For Meteorol*. 2020;292–293:108131. <https://doi.org/10.1016/j.agrformet.2020.108131>
 28. Zhou S, Liu Z, Chen F. Developing the DSSAT-CERES-Millet model for dynamic simulation of grain protein and starch accumulation in foxtail millet under varying irrigation and nitrogen regimes. *Plants*. 2025;14(6):60910. <https://doi.org/10.3390/plants14060910>
 29. Traoré B, Birhanu BZ, Sangaré S, Gumma MK, Whitbread AM. Contribution of climate-smart agriculture technologies to food self-sufficiency of smallholders in Mali. *Sustainability*. 2021;13(14):7757. <https://doi.org/10.3390/su13147757>
 30. Musara JP, Bahta YT, Musemwa L, Manzvera J. Rethinking climate-smart agriculture practices for productivity and income gains in Zimbabwe drylands. *Front Sustain Food Syst*. 2022;6:939595. <https://doi.org/10.3389/fsufs.2022.939595>
 31. Muskan F, Redhu M, Kumar R, Yadav RK, Singh R. Global millet market trends, production dynamics and future prospects under climate change. *Food Prod Process Nutr*. 2025;7(1):316. <https://doi.org/10.1186/s43014-025-00316-1>
 32. Nagaraja TE, Parveen SG, Prashanth KM, Ramesh N, Raghavendra S. Role of millets in climate-resilient agriculture and sustainable food systems. *Indian J Genet Plant Breed*. 2024;84(1):1–37. <https://doi.org/10.31742/ISGPB.84.1.1>
 33. Negri L, Bosi S, Santelli S, Tosti G, Benincasa P. Millets in Mediterranean cropping systems: Potential for sustainable and climate-resilient agriculture. *Field Crops Res*. 2024;318:109563. <https://doi.org/10.1016/j.fcr.2024.109563>
 34. Radeny M, Rao EJO, Notenbaert A, Girvetz E, Dengel C, Appiah K, et al. Climate-smart agriculture and its impact on food security and resilience of smallholder farmers. *Food Secur*. 2022;14(6):1511–35. <https://doi.org/10.1007/s12571-022-01307-7>
 35. Yiridomoh GY, Bonye SZ, Ahmed A, Derbile EK, Kombat EO. Adoption of climate-smart agriculture practices: A systematic review of determinants and impacts. *Clim Resil Sustain*. 2025;4(2):70017. <https://doi.org/10.1002/cli2.70017>
 36. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*. 2021;372:n71. <https://doi.org/10.1136/bmj.n71>
 37. Okolie CC, Nnam VE, Adelaja AO, Olagunju KO, Ajibola AA. Climate-smart agriculture research trends: A global bibliometric analysis. *Land*. 2023;12(1):50. <https://doi.org/10.3390/land12010050>
 38. Ndayisaba PC, Kuyah S, Midega CAO, Mwangi PN, Khan ZR. Push-pull technology enhances resilience to climate change and prevents land degradation. *Farming Syst*. 2023;1(2):100020. <https://doi.org/10.1016/j.farsys.2023.100020>
 39. Panjala P, Reddi VRM, Gumma MK, Deevi KC, Gupta SK. Identifying prospects for introducing pearl millet stress-tolerant cultivars in Rajasthan. *Smart Agric Technol*. 2023;6:100374. <https://doi.org/10.1016/j.atech.2023.100374>
 40. Traore B, Moussa AA, Traore A, Nassirou YSA, Ba MN, Tabo R. Pearl millet seedlings transplanting as a climate adaptation option for smallholder farmers in Niger. *Atmosphere*. 2022;13(7):997. <https://doi.org/10.3390/atmos13070997>
 41. Uppal RK, Wani SP, Garg KK, Alagarwamy G. Balanced nutrition increases yield of pearl millet under drought conditions. *Field Crops Res*. 2015;177:86–97. <https://doi.org/10.1016/j.fcr.2015.03.006>
 42. Thapa B, Awal R, Singh R, Karki S, Bista P, Panday D. Improving soil health and crop productivity through biochar and organic amendments under climate-smart agriculture. *Soil Sci Soc Am J*. 2025;89(5):e70129. <https://doi.org/10.1002/saj2.70129>
 43. Sissoko P, Guindo SS, Togola S, Dembélé BD, Grimsby LK, Aune JB. Climate-smart agriculture technologies and cereal production in Mali. *Agriculture*. 2023;13(6):1196. <https://doi.org/10.3390/agriculture13061196>
 44. Tomar PS, Verma SK, Gupta N, Bansal KN. Effect of long-term integrated nutrient management on productivity of pearl millet-mustard cropping system and soil fertility. *J Indian Soc Soil Sci*. 2018;66(3):295–99. <https://doi.org/10.5958/0974-0228.2018.00036.1>
 45. Tambol T, Derbile EK, Soulé M. Use of climate-smart agriculture technologies in West Africa peri-urban Sahel in Niger. *Sci Rep*. 2025;15(1):82813. <https://doi.org/10.1038/s41598-024-82813-w>
 46. Paul J, Rosado-Serrano A. Gradual internationalization vs born-global/international new venture models: A review and research agenda. *Int Mark Rev*. 2019;36(6):830–58. <https://doi.org/10.1108/IMR-10-2018-0280>
 47. Mukherjee B, Jha RK, Singh A, Kumar R, Prasad R. Millets as climate-resilient crops for sustainable agriculture in climate-vulnerable regions. *Front Plant Sci*. 2025;16:1574699. <https://doi.org/10.3389/fpls.2025.1574699>
 48. Sanou J, Bationo BA, Barry S, Bayala J, Zougmore R. Combining soil fertilisation, cropping systems and improved varieties in Burkina Faso. *Agric Food Secur*. 2016;5(1):7. <https://doi.org/10.1186/s40066-016-0067-3>
 49. Silungwe FR, Graef F, Bellingrath-Kimura SD, Tumbo SD, Kahimba FC, Lana MA. Management strategies of pearl millet farmers to cope with rainfall variability. *Agronomy*. 2019;9(7):400. <https://doi.org/10.3390/agronomy9070400>
 50. Kugedera AT, Kokerai LK, Nyamadzawo G, Mandumbu R. Evaluating water conservation techniques and manure effects on sorghum yield and water use efficiency. *Heliyon*. 2024;10(12):e33032. <https://doi.org/10.1016/j.heliyon.2024.e33032>
 51. Cui L, Lu J, Ding S, Song X, Chen P, Feng B, et al. Optimizing ridge-furrow mulching patterns improves resource use efficiency and yield of millet. *Agric Water Manag*. 2025;312:109415. <https://doi.org/10.1016/j.agwat.2025.109415>
 52. Chandana P, Madhavi Lata A, Prasad JVNS, Aariff Khan MA. Greenhouse gas emissions from integrated nutrient management practices in pearl millet + *Melia dubia* agri-silvi system. *Curr Sci*. 2021;121(5):704–8. <https://doi.org/10.18520/cs/v121/i5/704-708>
 53. Riahi L, Ben-Romdhane M, Masmoudi AS. Industrial relevance of pearl millet as a climate-smart cereal. *J Plant Biotechnol*. 2024;51(2):77–88. <https://doi.org/10.5010/JPB.2024.51.009.077>
 54. Mehla N, Singh P, Rathore VS, Yadav RK. Assessment of water footprint for major crops in Banas River Basin of Rajasthan. *J Appl Nat Sci*. 2022;14(4):1264–71. <https://doi.org/10.31018/jans.v14i4.3896>
 55. Vincent A, Balasubramani N. Climate-smart agriculture and extension advisory service stakeholders' prioritisation in Anantapur district. *J Water Clim Change*. 2021;12(8):3915–31. <https://doi.org/10.2166/wcc.2021.329>
 56. Zagre I, Akinseye FM, Worou ON, Kone M, Faye A. Climate change adaptation strategies among smallholder farmers in Senegal's semi-arid zone. *Front Clim*. 2024;6:1332196. <https://doi.org/10.3389/fclim.2024.1332196>
 57. Zagre P, Sall A, Faye M, Ndiaye O, Diouf M. Simulation of pearl millet growth and yield using DSSAT-CERES-millet model across diverse agro-ecological environments. *CABI Agric Biosci*. 2025;6(1):11. <https://doi.org/10.1079/ab.2025.0011>

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonpublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc

See https://horizonpublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.