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DETERMINANTS AND OUTCOMES OF CLIMATE-SMART AGRICULTURE ADOPTION AMONG FARMERS: A BIBLIOMETRIC AND THEMATIC REVIEW

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ABSTRACT
Climate change poses an escalating threat to smallholder and commercial agriculture alike, prompting a rapidly expanding body of research on how farmers perceive, adopt and benefit from climate-smart agriculture (CSA) and related adaptation practices. This review combines a bibliometric analysis with a comprehensive thematic synthesis of 138 peer-reviewed, open-access journal articles indexed in Scopus and published between 2015 and 2025. Using Biblioshiny and VOSviewer outputs for annual scientific production, source and country contributions and keyword co-occurrence networks, the review first maps the intellectual structure of the field. It then synthesises findings across six recurring themes: the socio-economic and institutional determinants of CSA adoption; gender dimensions of access and use; barriers and constraints; the range of CSA practices and adaptation strategies documented; impacts on productivity, income, food security and livelihoods; and the methodological approaches used to study adoption behaviour. The literature is heavily concentrated in Sub-Saharan Africa and South/Southeast Asia, dominated by cross-sectional household-survey designs analysed with binary, multivariate and ordered probit or logit models, with an emerging but still limited use of experimental and life-cycle approaches. Findings converge on a consistent set of adoption drivers-extension access, credit, land tenure security, farmer organisations, education and prior climate-risk experience-while gender, tenure and information asymmetries remain persistent constraints. The review concludes by identifying methodological, geographic and conceptual gaps, including a shortage of longitudinal and quasi-experimental impact evaluations, limited attention to Latin America and Central Asia and inconsistent conceptualisation of adoption itself and outlines priorities for future research and policy.

KEYWORDS: climate-smart agriculture; climate change adaptation; smallholder farmers; adoption determinants; bibliometric analysis; food security.

1. INTRODUCTION
Agriculture remains one of the sectors most exposed to the physical and economic consequences of climate change and it is simultaneously a major source of greenhouse gas emissions. Rising temperatures, erratic rainfall and an increasing frequency of extreme weather events are already altering crop yields, water availability and pest and disease pressure across both rain-fed and irrigated farming systems (Niles et al., 2015; Grimberg et al., 2018). Farm households, particularly smallholders in Sub-Saharan Africa and South and Southeast Asia, are disproportionately vulnerable because their livelihoods depend directly on climate-sensitive production and because their capacity to absorb shocks is often constrained by limited assets, weak market access and thin safety nets (García de Jalón et al., 2018; Mairura et al., 2021). In response, the concept of climate-smart agriculture (CSA) has become a central organising framework for research, donor programming and national policy. First articulated by the Food and Agriculture Organization, CSA is generally understood as an integrated approach pursuing three simultaneous objectives: sustainably increasing agricultural productivity and incomes, adapting and building resilience to climate change and reducing or removing greenhouse gas emissions where possible (Verschuuren, 2018; Abegunde & Obi, 2022). In practice, CSA is not a single technology but a bundle of practices-ranging from drought-tolerant varieties, conservation agriculture and agroforestry to water-harvesting, integrated soil-fertility management and climate information services-selected to fit specific agroecological and socio-economic contexts (Khatri-Chhetri et al., 2017; Lopez-Ridaura et al., 2018).
Over the past decade, an expanding empirical literature has examined how and why farmers adopt CSA practices and other autonomous adaptation strategies, what constrains uptake and what outcomes adoption produces for productivity, income, food security and resilience. This literature spans multiple disciplines-agricultural economics, extension science, geography, environmental policy and gender studies-and has grown particularly quickly since 2021, coinciding with renewed international attention to climate finance and the Sustainable Development Goals (SDG 2 on food security and

SDG 13 on climate action). Despite this growth, the field remains fragmented: studies use different definitions of "adoption," different bundles of practices and different econometric or psychometric frameworks, making it difficult to draw cumulative, policy-relevant conclusions (Hermans et al., 2021; Rodríguez-Barillas et al., 2024b).

Bibliometric methods offer a way to systematically map this fragmented landscape-identifying the most productive sources, countries and thematic clusters-while a complementary narrative synthesis can surface the substantive findings that a purely quantitative mapping cannot capture. Several narrower reviews exist on specific CSA sub-topics or regions (Abegunde & Obi, 2022; Tadesse & Ahmed, 2023), but a combined bibliometric-and-thematic review that integrates the full breadth of farmer-level adoption, gender, barrier and impact studies published in the last decade is still lacking.

This review therefore pursues two complementary objectives. First, it provides a bibliometric overview of the CSA and climate-adaptation literature indexed in Scopus between 2015 and 2025, describing patterns of annual scientific production, leading journals and contributing countries and the thematic structure revealed by keyword co-occurrence and cluster analysis. Second, it synthesises the substantive findings of the underlying studies around six themes: (i) socio-economic and institutional determinants of adoption; (ii) gender dimensions of access and use; (iii) barriers and constraints; (iv) the range of CSA practices and adaptation strategies documented in the literature; (v) impacts on productivity, income, food security and livelihoods; and (vi) the methodological approaches used to study farmer decision-making. The review closes by identifying gaps in geographic coverage, methodology and conceptual clarity and by outlining priorities for future research and for policy and extension practice aimed at accelerating climate-resilient agricultural transitions.

2. METHODOLOGY

This review follows a two-stage design combining bibliometric mapping with a qualitative thematic synthesis, based on a systematically retrieved and filtered corpus of journal articles from the Scopus database. This study utilizes the PRISMA 2020 framework (Fig.1.) which includes identification, screening and inclusion stages of the studies used in this review.

2.1. Search strategy and database

Scopus was searched using a combined string targeting climate-smart agriculture, adaptation technologies and practices, farmers and farm households and the outcomes of adoption and assessment in crop and agricultural systems. The search string used was: ("climate-smart agriculture" OR "adaptation technolog*" OR "adaptation practice*") AND ("farmer*" OR "farm household*") AND ("adoption" OR "assessment") AND ("crop" OR "agriculture"), applied to article title, abstract and keywords. The initial search returned 848 documents.

2.2. Screening and eligibility criteria

A time filter restricting publication years to 2015-2025 reduced the corpus to 705 articles, ensuring the review captures the decade of literature that followed the CSA concept. Further filters were then applied in sequence: subject area (Agricultural and Biological Sciences and Social Sciences), document type (article only, excluding conference papers, book chapters, reviews-as-secondary-sources and notes), source type (journal), language (English), publication stage (final, excluding articles in press) and open access status (all open-access categories). After applying these filters, the final corpus comprised 138 documents, forming the basis for both the bibliometric analysis and the thematic synthesis reported in Table 1.

Table 1. Inclusion and Exclusion criteria

Criteria	Inclusion	Exclusion
Database	Records indexed in Scopus	Records not indexed in Scopus
Publication year	2015–2025	Published before 2015 or after 2025
Subject area	Agricultural and Biological Sciences; Social Sciences	All other Scopus subject areas (e.g., Environmental Science only, Medicine, Engineering, etc., with no overlap in the two included areas)
Document type	Article	Conference paper, book chapter, review (as a secondary/non-original source), note, editorial, erratum, short survey
Source type	Journal	Conference proceedings, books, book series, trade journals
Language	English	Non-English publications
Publication stage	Final	Article in press

2.3. Bibliometric analysis

The corpus, was analysed using Biblioshiny (the R Bibliometrix web interface) and VOSviewer. Biblioshiny was used to generate annual scientific production trends, the most relevant publication sources, country-level scientific production (based on corresponding-author affiliations), a keyword frequency word cloud and a thematic map derived from keyword co-occurrence clustering (Louvain community detection on the merged author- and index-keyword network). VOSviewer was used to construct and visualise the keyword co-occurrence network shown in Figure 1, in which node size reflects term frequency, colour reflects cluster membership and edge thickness reflects co-occurrence strength.

2.4. Thematic synthesis

In parallel, titles, abstracts and author keywords for all 138 articles were read and coded inductively to identify recurring substantive themes. Six themes emerged and structure the results and discussion below: determinants of CSA adoption; gender dimensions; barriers and constraints; the range of practices and strategies studied; impacts on productivity, income, food security and livelihoods; and methodological approaches. Every study cited in the synthesis is drawn exclusively from the 138-document corpus described above; no external sources outside this set were introduced into the substantive findings.

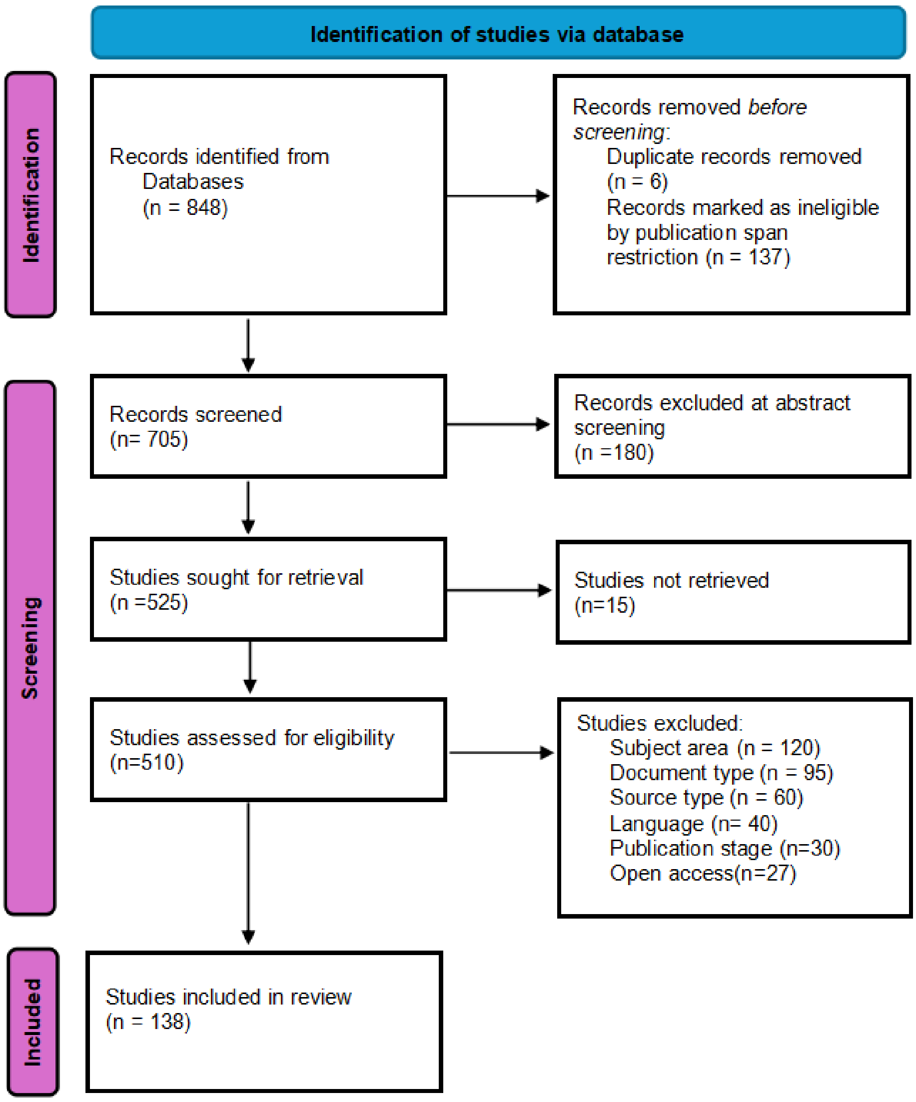

Fig.1. PRISMA 2020 flow diagram of the identification, screening, eligibility assessment, and inclusion of studies

3. BIBLIOMETRIC RESULTS

The bibliometric profile of the 138-document corpus is described below in terms of annual scientific production, contributing sources and countries and the thematic structure of the field revealed by keyword co-occurrence analysis.

3.1 Annual scientific production

The annual scientific production on CSA adoption is presented in Fig. 2. Publication of research meeting the review's eligibility criteria was sparse and stable between 2015 and 2020 (two to nine articles per year) before rising sharply from 2021 onward. The corpus contains 2 articles in 2015, 2 in 2016, 2 in 2017, 9 in 2018, 9 in 2019, 5 in 2020, 24 in 2021, 7 in 2022, 20 in 2023, 27 in 2024 and 31 in the partial year 2025. Over 75% of the eligible open-access articles were published from 2021 onward, indicating that farmer-level CSA adoption research is a fast-growing and still-accelerating field, likely reflecting both the maturation of national CSA programmes launched in the mid-2010s and the increasing availability of open-access publishing options that made these studies eligible for inclusion in this review.

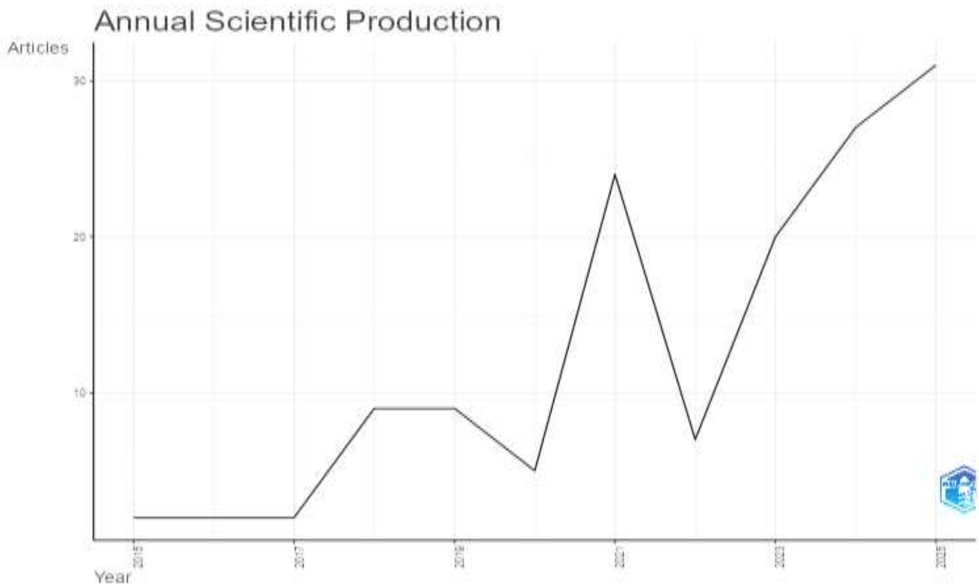

Fig.2. Annual Scientific Production of articles from 2000 to 2025 on CSA adoption research

3.2 Most relevant sources

Publication is dispersed across a large number of journals, but a small set of outlets account for a disproportionate share of the corpus which is illustrated in Fig.3. Sustainability (Switzerland) is the leading source with 19 articles, followed by Frontiers in Sustainable Food Systems (11), Agricultural Systems (10), Discover Sustainability (7) and the Indian Journal of Extension Education (5). Cogent Food and Agriculture and Land Use Policy each contributed 4 articles, while Agronomy, Climate Risk Management, the International Journal of Agricultural Sustainability and the International Journal of Climate Change Strategies and Management each contributed 3. The concentration of publications in multidisciplinary sustainability and food-systems journals, rather than in discipline-specific agricultural economics or extension outlets, reflects the applied, policy-oriented character of most CSA adoption research.

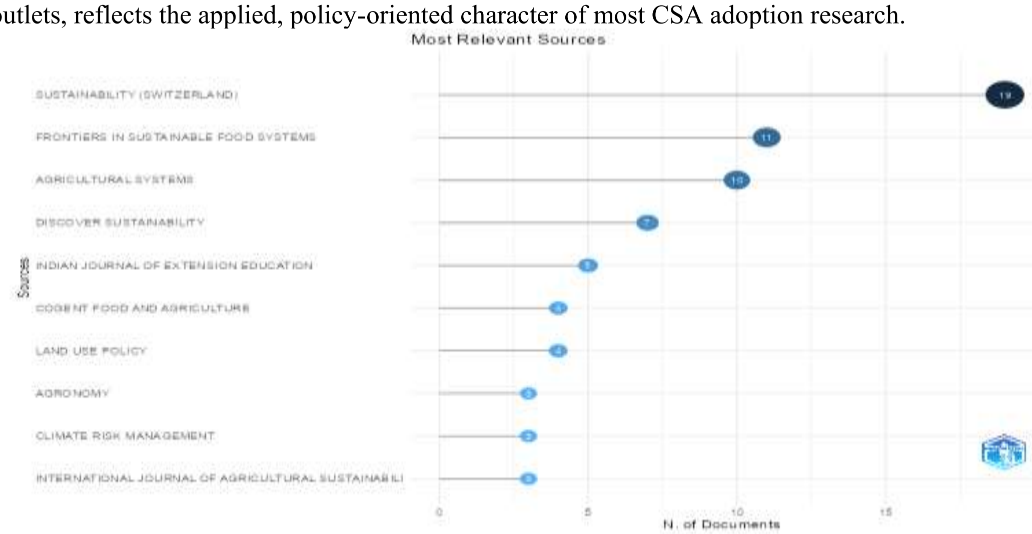

Fig.3. Most relevant sources of articles under CSA adoption research

3.3 Country scientific production

The country-wise scientific production on CSA adoption studies is represented in Fig.4. Corresponding-author affiliations show research leadership concentrated in a mix of high-income countries providing research capacity and funding and low and middle-income countries providing the empirical study settings. The United States leads with 56 contributions, followed by Kenya (47), India (33), Ethiopia (27), China (21), South Africa (21), the Netherlands (20) and the United Kingdom (20). France (15), Ghana (15), Bangladesh (14) and Germany (13) also feature prominently, with smaller but notable contributions from Pakistan, Costa Rica and the Philippines. This pattern indicates strong North-South research collaboration, with East and Southern African countries (Kenya, Ethiopia, South Africa) and South Asian countries (India, Bangladesh, Pakistan) serving as the dominant empirical settings for smallholder CSA adoption research, consistent with the geographic exposure of these regions to climate variability and the concentration of CSA investment programmes (for example, the CGIAR Climate-Smart Villages initiative) in these areas.

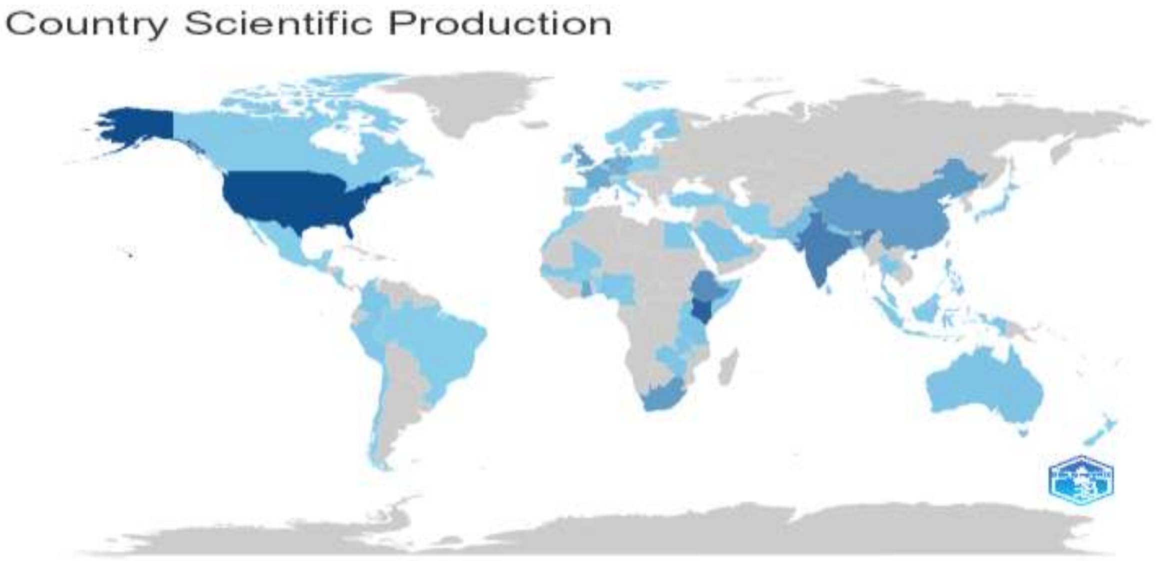

Fig.4. Country scientific production map depicting areas of CSA adoption research

3.4 Keyword co-occurrence and thematic map

The word cloud generated from author and index keywords (Fig.5.) confirms that climate change (121 occurrences) and climate-smart agriculture (50 occurrences) are the dominant terms, followed by adaptation (34), smallholder (29), food security (28), adaptive management and technology adoption (25 each), adoption (18), agriculture (18) and climate smart agriculture as a variant phrase (18). Secondary but recurrent terms include alternative agriculture, crop production, agricultural practice and agricultural technology, underscoring that the corpus centres on farm-level decision-making regarding discrete, identifiable practices rather than on macro-level climate policy.

Fig.5. Word cloud visualization based on the keywords of compiled literature

The VOSviewer keyword co-occurrence network (Fig.6.) visually corroborates this structure, showing climate-smart agriculture and climate change as the two largest, most central nodes, densely connected to adoption, adaptation, smallholder, gender, farmers, mitigation and resilience, with secondary clusters oriented toward specific countries (Kenya, Tanzania, Ethiopia, Ghana, Bangladesh, sub-Saharan Africa) and methodological terms (multivariate probit model). The proximity and strong linkage between "climate-smart agriculture" and "climate change" nodes indicates that, in this literature, CSA is treated principally as an operational vehicle for climate change adaptation rather than as a separate or competing paradigm.

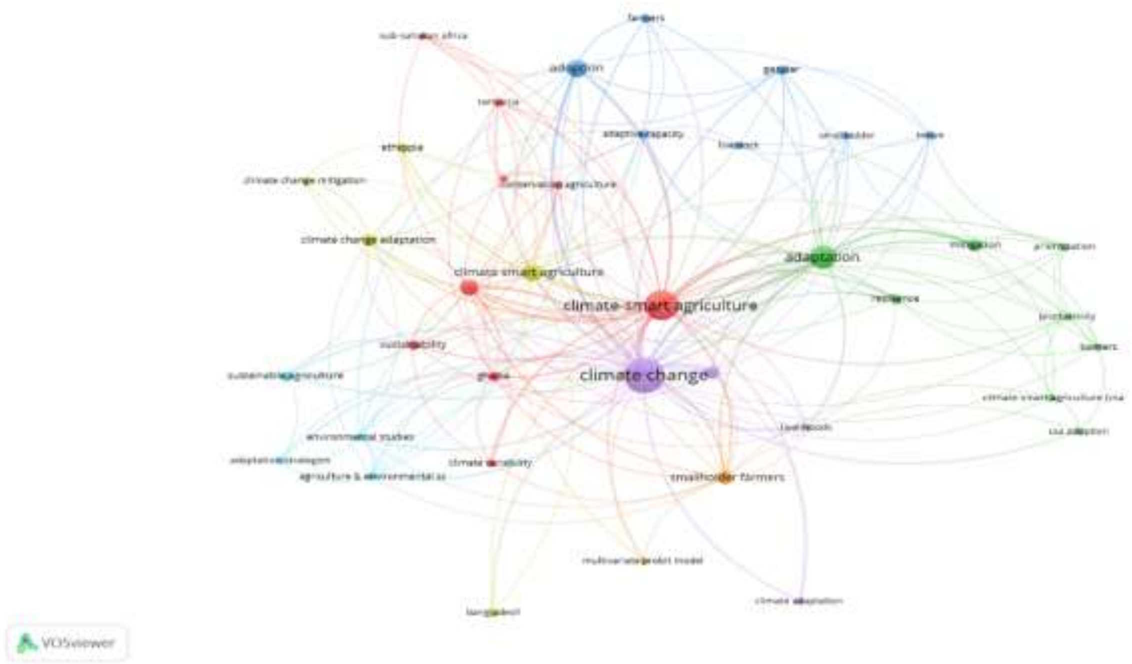

Fig.6. VOSviewer keyword co-occurrence network of the 138-document corpus.

The Biblioshiny thematic map (Fig.7.) decomposes the keyword network (n = 250 keywords, minimum frequency 2) into seven Louvain-detected clusters, summarised in Table 2. The largest cluster is organised around climate change (121 occurrences) and climate-smart agriculture (50) and also contains agricultural extension, resilience, gender and several country terms (Ghana, Tanzania, Bangladesh), reflecting the centrality of extension-mediated technology transfer in this literature. A second cluster centres on adaptation (34) and smallholder (29), linking to agricultural practice, mitigation, innovation and Ethiopia and Kenya as leading country contexts and includes methodological markers such as the multivariate probit model, reflecting the econometric tradition of modelling correlated adoption decisions across multiple practices simultaneously. A third cluster is anchored by food security (28) and alternative/sustainable agriculture, connecting to farming system, crop yield, drought, irrigation and India and Nepal. A fourth cluster, centred on adaptive management and technology adoption (25 occurrences each), captures perception, climate change adaptation, farmers' knowledge, adaptive capacity and risk assessment - the psychological and cognitive determinants of adoption behaviour. A fifth cluster organised around adoption, agriculture and climate smart agriculture (18 occurrences each) includes productivity, sub-Saharan Africa, climate resilience and social capital. A sixth cluster centred on crop production (16) and agricultural technology (15) includes decision-making, agricultural policy, livelihood and Pakistan. A seventh, smaller cluster reflects the disciplinary self-labelling of some sources as "agriculture & environmental sciences." Centrality-density (Callon) statistics place the food-security cluster as having both the highest centrality (15.6) and the highest density (82.3) among the substantive clusters, suggesting it functions as an already well-developed sub-field tightly linked to the rest of the network.

Table 2. Thematic clusters from keyword co-occurrence analysis (Biblioshiny)

Cluster	Label	Leading keywords (occurrences)
1	Climate change	climate change (121), climate-smart agriculture (50), agricultural extension (9), resilience (7), gender (6)
2	Adaptation	adaptation (34), smallholder (29), agricultural practice (15), mitigation (13), Ethiopia (10), Kenya (7)
3	Food security	food security (28), alternative agriculture (17), farming system (11), sustainability (11), crop yield (6)
4	Adaptive management	adaptive management (25), technology adoption (25), perception (14), climate change adaptation (10)
5	Adoption	adoption (18), agriculture (18), climate smart agriculture (18), productivity (5), sub-Saharan Africa (4)
6	Crop production	crop production (16), agricultural technology (15), decision making (10), agricultural policy (9)
7	Agriculture & environmental sciences	agriculture & environmental sciences (3), environmental studies (3), environmental management (2)

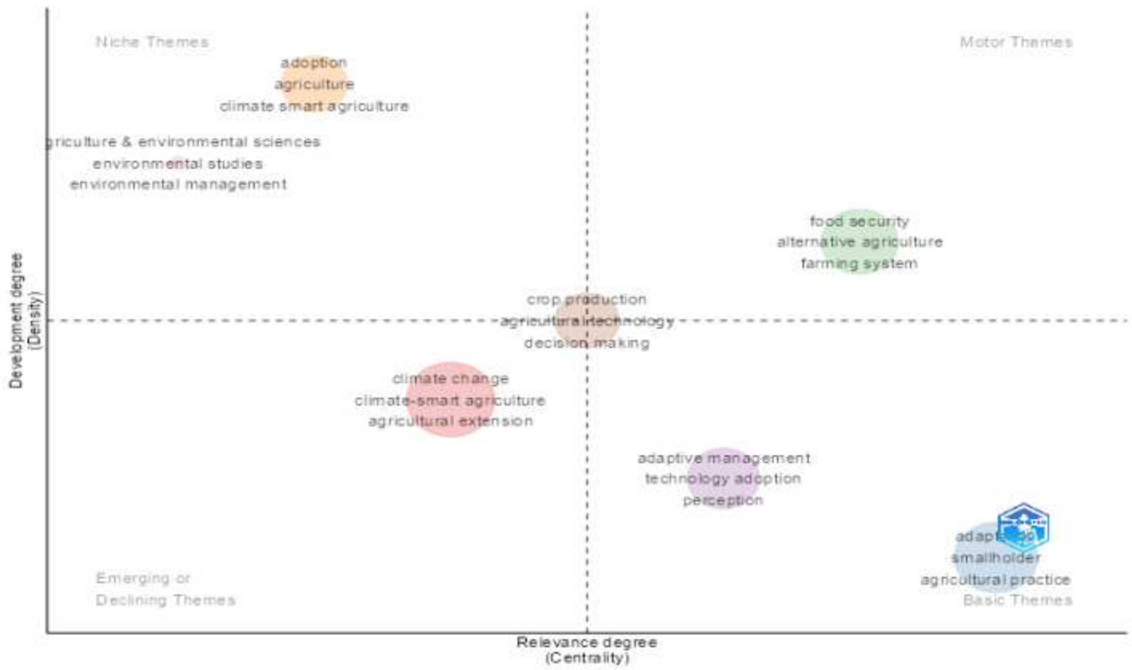

Fig.7. Thematic mapping of the compiled literature

3.5 Representative and influential studies

Consistent with the thematic clustering, the individual studies most frequently associated with the "determinants of adoption" in the corpus include county- and district-level adoption studies from South Africa (Abegunde et al., 2020), Kenya (Kangogo et al., 2021; Muriithi Lydia et al., 2021; Waaswa et al., 2021), Ethiopia (Sisay et al., 2023; Kassa & Abdi, 2022; Zeleke et al., 2024) and Ghana (Antwi-Agyei et al., 2021b), together with the methodological and prioritisation studies conducted under the CGIAR Climate-Smart Villages programme in Nepal, Mali and the Nyando basin of Kenya (Ghimire et al., 2022; Ouédraogo et al., 2019; Njogu et al., 2024). These recurring studies anchor the thematic clusters identified above and are discussed in depth in the sections that follow.

4. THEMATIC RESULTS

Beyond the bibliometric structure described above, close reading of the 138 articles reveals a set of recurring substantive findings that cut across countries and crops. This section synthesises these findings around six themes: determinants of CSA adoption; gender dimensions of access and use; barriers and constraints; the range of practices and adaptation strategies studied; impacts on productivity, income, food security and livelihoods; and the methodological approaches used to study farmer decision-making.

4.1. Socio-economic and institutional determinants of adoption

A large share of the corpus is dedicated to identifying the household, farm and institutional characteristics associated with CSA adoption. Across highly diverse settings, several determinants recur with notable consistency. Access to agricultural extension services and information is repeatedly identified as one of the strongest predictors of adoption, whether measured through direct extension contact, participation in farmer field schools, or exposure to climate information services (Waaswa et al., 2024; Sisay et al., 2023; Jatav, 2024). Education level, farming experience and household labour endowment also emerge consistently as positive correlates of adoption in studies from South Africa, Kenya, Ethiopia and Pakistan (Abegunde et al., 2020; Mthethwa et al., 2022; Mustafa et al., 2024).

Access to credit, land tenure security and farm size are similarly prominent. Secure land rights and formal land certification are associated with greater willingness to invest in longer-term soil and water conservation measures, as demonstrated in studies using satellite-derived productivity data following Ethiopia's land tenure reform (Rampa & Lovo, 2023) and in Malawian conservation-agriculture research examining how land tenure structures interact with technology adoption (Jew et al., 2020). Farmer entrepreneurship and market orientation have also been shown to matter: farmers who are more entrepreneurially oriented and better connected to output markets are more likely to adopt CSA bundles, as documented among Kenyan smallholders (Kangogo et al., 2021).

Social capital, group membership and participation in farmer organisations or climate-smart village programmes consistently increase the likelihood and intensity of adoption. Evidence from Burkina Faso links social capital directly to climate-change adaptation decisions (Yaméogo et al., 2018), while studies of the CGIAR Climate-Smart Villages in Mali, Nepal and the Nyando basin of Kenya show that structured, community-based scaling mechanisms and institutional innovations raise both actual and potential adoption rates (Ouédraogo et al., 2019; Ghimire et al., 2022; Njogu et al., 2024). Institutional determinants including access to input and output markets, cooperative membership and local governance quality are further emphasised in Kenyan and Ethiopian studies examining the institutional architecture surrounding CSA uptake (Waaswa et al., 2024; Waaswa et al., 2021; Takele et al., 2023).

Farmers' risk perceptions and prior experience of climate shocks are also robust predictors. Perceived climate variability, direct experience of drought or flooding and subjective assessments of climate risk increase the probability of adopting protective practices in Kenya, Nigeria, Nordic Europe and Central America (Mairura et al., 2021; Ayanlade et al., 2018; Käyhkö, 2019; de Sousa et al., 2018). Behavioural and psychological drivers - including self-efficacy, attitudes and perceived behavioural control - feature increasingly in more recent studies that move beyond purely socio-economic covariates, for instance in analyses of Kenyan livestock farmers' adoption intentions (Chepng′etich et al., 2025) and of the policy-environment interactions shaping Central American farmers' acceptance of climate-smart technologies (Rodríguez-Barillas et al., 2024b).

Farm-level biophysical and structural characteristics - such as farm size, plot fragmentation, soil quality and access to irrigation - also condition adoption decisions, as shown in studies of Californian (Johnson et al., 2023a) and Chinese (Wang et al., 2025) farmers and interact with household wealth in shaping which practices and how many, a household can afford to adopt simultaneously (Makate et al., 2019).

Table 3. Categories of socio-economic and institutional determinants of CSA adoption

Determinant category	Specific factors	Representative studies
Human capital & information	Education, farming experience, extension contact, climate information access	(Waaswa et al., 2024); (Sisay et al., 2023); (Jatav, 2024)
Financial & land assets	Credit access, land tenure security, farm size, land certification	(Rampa & Lovo, 2023); (Jew et al., 2020); (Abegunde et al., 2020)
Market orientation & entrepreneurship	Output market access, entrepreneurial orientation, cost efficiency	(Kangogo et al., 2021); (Mustafa et al., 2024)
Social capital & institutions	Group membership, cooperative participation, climate-smart village programmes, local governance	(Yaméogo et al., 2018); (Ouédraogo et al., 2019); (Ghimire et al., 2022); (Njogu et al., 2024); (Waaswa et al., 2021); (Takele et al., 2023)
Risk perception & experience	Perceived climate variability, prior shock experience, subjective risk assessment	(Mairura et al., 2021); (Ayanlade et al., 2018); (Käyhkö, 2019); (de Sousa et al., 2018)
Behavioural & psychological factors	Self-efficacy, attitudes, perceived behavioural control, policy-environment interaction	(Chepng′etich et al., 2025); (Rodríguez-Barillas et al., 2024b)
Farm structural characteristics	Farm size, plot fragmentation, soil quality, irrigation access	(Johnson et al., 2023a); (Wang et al., 2025); (Makate et al., 2019)

4.2. Gender dimensions of CSA access, use and outcomes

Gender emerges as one of the most consistently examined cross-cutting themes in the corpus, reflecting sustained attention to differentiated vulnerability and agency between men and women farmers. Multiple studies document that women smallholders face distinct and often more binding constraints in accessing CSA technologies, information and complementary inputs than their male counterparts. In Malawi, women smallholders face specific technology and labour-productivity constraints that limit uptake of climate-smart practices (Murray et al., 2016), while research in Burundi identifies persistent gender norms restricting women's access to and use of CSA technology (Nchanji et al., 2023) and parallel work in Tanzania documents gender disparities in access and use of CSA more broadly (Nchanji et al., 2025).

Several studies move beyond documenting disparities to examine their drivers and consequences. Evidence from Latin American climate-smart villages shows that women's access to CSA interventions is shaped by intra-household decision-making dynamics and differentiated extension outreach (Acosta et al., 2021), while research from Tanzania's semi-arid Dodoma region explores the gender dynamics underlying adoption decisions in more depth, highlighting the role of intra-household bargaining and labour allocation (Awoke et al., 2024). Studies from Nigeria and Vietnam quantify the distributional welfare effects of gendered CSA adoption, finding that gender differentials translate into measurable differences in farm production and household welfare outcomes (Daudu et al., 2025) and in ethnicity- and gender-sensitive adaptation options (Anh & Le Vinh, 2025; Nhat Lam Duyen et al., 2021). Complementary work on gender and agricultural policy in India examines how national CSA policy frameworks address (or fail to address) gender equity considerations (Barooah et al., 2023).

Collectively, these studies indicate that gender-blind CSA promotion risks reproducing or widening existing inequalities in access to land, credit, extension and labour and that closing these gaps requires deliberate design choices in programme targeting, extension delivery and technology selection rather than treating gender as a residual control variable in adoption models.

Table 4. Gender-related findings on CSA access, use and outcomes

Country / context	Key gender-related finding	Study
Malawi	Women smallholders face distinct technology and labour-productivity constraints limiting CSA uptake	(Murray et al., 2016)
Burundi	Persistent gender norms restrict women's access to and use of CSA technology	(Nchanji et al., 2023)

Southern Tanzania	Gender disparities documented in access to and use of CSA more broadly	(Nchanji et al., 2025)
Latin American climate-smart villages	Women's access shaped by intra-household decision-making and differentiated extension outreach	(Acosta et al., 2021)
Semi-arid Dodoma, Tanzania	Intra-household bargaining and labour allocation shape gendered adoption decisions	(Awoke et al., 2024)
Nigeria	Gender differentials produce measurable differences in farm production and household welfare	(Daudu et al., 2025)
Vietnam	Ethnicity- and gender-sensitive design shapes uptake of CSA options; gender and youth issues vary by region	(Anh & Le Vinh, 2025); (Nhat Lam Duyen et al., 2021)
India	National CSA policy frameworks inconsistently address gender equity considerations	(Barooah et al., 2023)

4.3. Barriers and constraints to adoption

A substantial subset of the literature focuses explicitly on the barriers that prevent farmers from adopting CSA practices even where objective agronomic and economic benefits exist. Financial constraints - including limited access to credit, high upfront investment costs and thin savings buffers - are the most frequently cited barrier, documented in Ghana (Antwi-Agyei et al., 2021b), Kenya (Autio et al., 2021) and China's Loess Plateau and Black Soil regions (Wang et al., 2025). Limited access to extension services, weak dissemination of climate information and low awareness of available technologies constitute a second recurring barrier category, examined through household surveys among paddy farmers in India (Mishra & Malik, 2024b) and through California-based interviews with technical-assistance providers who themselves identify the barriers producers face (Johnson et al., 2023b).

Institutional and policy-level barriers also feature prominently. Research examining whether local development plans in semi-arid Ghana adequately mainstream CSA finds that policy documents often fail to translate national CSA rhetoric into actionable local programming (Diko et al., 2021), while an assessment of India's national CSA effort catalogues overlapping regulatory, infrastructural and market barriers constraining scale-up (Tankha et al., 2020). Land tenure insecurity, fragmented landholdings and unclear property rights are identified as structural barriers in Malawi (Jew et al., 2020) and in broader African food-systems assessments (Dougill et al., 2021).

A smaller but conceptually important set of studies critiques the framing of "barriers" and "adoption" itself, arguing that binary adopt/non-adopt framings obscure the situated, often rational reasons why farmers reject, modify, or partially adopt recommended practices and calling for adoption research to engage more directly with farmers' own agency and knowledge systems (Hermans et al., 2021; Vernooij et al., 2024). Multidimensional barrier frameworks that combine financial, informational, institutional and behavioural dimensions, as applied in Northeast China, illustrate one response to this critique by explicitly modelling barriers as an interacting system rather than a list of independent obstacles (Wang et al., 2025).

Table 5. Categories of barriers and constraints to CSA adoption

Barrier type	Typical manifestation	Representative studies
Financial	Limited credit access, high upfront investment costs, thin savings buffers	(Antwi-Agyei et al., 2021b); (Autio et al., 2021); (Wang et al., 2025)
Informational / extension	Weak dissemination of climate information, low technology awareness	(Mishra & Malik, 2024b); (Johnson et al., 2023b)
Institutional / policy	Local plans fail to mainstream CSA; overlapping regulatory and market barriers	(Diko et al., 2021); (Tankha et al., 2020)
Land tenure & structural	Insecure tenure, fragmented holdings, unclear property rights	(Jew et al., 2020); (Dougill et al., 2021)
Conceptual / framing	Binary adopt/non-adopt framing obscures farmer agency and rational rejection or modification	(Hermans et al., 2021); (Vernooij et al., 2024)

4.4. CSA practices and adaptation strategies documented in the literature

The corpus documents a wide and heterogeneous portfolio of practices classified as climate-smart or adaptive. Soil and water conservation measures - including conservation agriculture, minimum tillage, terracing and small-scale irrigation - are the most commonly studied practice category, examined in Malawi (Jew et al., 2020; Musa et al., 2018), Zimbabwe (Makate et al., 2019), Ethiopia (Bojago & Abrham, 2023) and Botswana (Jagadeesh et al., 2024). Drought-tolerant and stress-resilient crop varieties feature prominently in maize-based systems across Southern and Eastern Africa (Mthethwa et al., 2022; Makate et al., 2019) and in rice systems in Vietnam and Nepal (Kodama et al., 2025; Pandeya et al., 2024).

Agroforestry and fertiliser-tree systems, integrated soil-fertility management and crop diversification represent a second recognisable cluster of practices, studied in Malawi (Musa et al., 2018), Zambia (Petros et al., 2025) and Nigeria (Kanu & Przezbórska-Skobiej, 2025). Livestock-oriented CSA practices - including improved feeding regimes under climate stress and intentions to adopt climate-smart livestock management - are examined in Kenya's arid and semi-arid lands (Chepng′etich et al., 2025; Vernooij et al., 2024) and in livestock-foodprint mitigation research from the United States (Lecuyer & Verrier, 2025).

Climate information services, early-warning systems and digital/AI-enabled decision-support tools constitute an emerging practice category, illustrated by an intuitive greenhouse-gas awareness platform for Thai farmers (Raksapatcharawong & Veerakachen, 2025) and by a review of artificial-intelligence applications for climate-smart agriculture and plant adaptation (Mandour et al., 2025). Institutional and policy-oriented "practices" - such as participatory technology co-design, role-playing games for social learning and structured multi-criteria prioritisation frameworks - are documented in Brazil (Salvini et al., 2016), across multiple West African sites through a co-design methodology (Andrieu et al., 2019) and in stakeholder-prioritisation exercises conducted in South Asia (Khatri-Chhetri et al., 2019) and Kenya (Khatri-Chhetri et al., 2017).

Several studies further show that farmers do not adopt practices in isolation but combine them into portfolios, with complementary and substitutable relationships among practices shaping overall CSA uptake, as demonstrated among flood-prone Bangladeshi farmers (Akter et al., 2023b) and among rice producers in Hubei, China, whose combined adoption of adaptive and mitigatory practices jointly affects yield and income (Liang et al., 2021).

Table 6. Categories of CSA practices and adaptation strategies documented in the corpus

Practice category	Examples	Representative studies
Soil & water conservation	Conservation agriculture, minimum tillage, terracing, small-scale irrigation	(Jew et al., 2020); (Musa et al., 2018); (Makate et al., 2019); (Bojago & Abrham, 2023); (Jagadeesh et al., 2024)
Stress-resilient varieties	Drought-tolerant maize, stress-resilient rice varieties	(Mthethwa et al., 2022); (Kodama et al., 2025); (Pandeya et al., 2024)
Agroforestry & soil fertility	Fertiliser trees/shrubs, integrated soil-fertility management, crop diversification	(Musa et al., 2018); (Petros et al., 2025); (Kanu & Przezbórska-Skobiej, 2025)
Livestock-oriented CSA	Climate-adapted feeding regimes, livestock-foodprint mitigation	(Chepng′etich et al., 2025); (Vernooij et al., 2024); (Lecuyer & Verrier, 2025)
Climate information & digital tools	GHG-awareness platforms, AI-enabled decision support	(Raksapatcharawong & Veerakachen, 2025); (Mandour et al., 2025)
Participatory / institutional practices	Role-playing games for social learning, co-design, stakeholder prioritisation frameworks	(Salvini et al., 2016); (Andrieu et al., 2019); (Khatri-Chhetri et al., 2019); (Khatri-Chhetri et al., 2017)
Practice bundles / portfolios	Complementary and substitutable combinations of adaptive and mitigatory practices	(Akter et al., 2023b); (Liang et al., 2021)

4.5. Impacts on productivity, income, food security and livelihoods

A substantial share of the literature moves beyond adoption determinants to assess the outcomes of CSA adoption. Productivity and yield effects are generally found to be positive, though magnitudes vary by practice and context: potato yields in Kenya rise with CSA technology adoption (Andati et al., 2023), wheat productivity and net returns improve in Pakistan (Mustafa et al., 2024; Bibi, 2025) and cotton production and associated livelihoods improve in Punjab (Imran et al., 2018). Economy-wide modelling in Ethiopia suggests that CSA adoption at scale can generate macroeconomic productivity gains beyond the farm level (Komarek et al., 2019).

Food security and dietary outcomes constitute a second major outcome category. Cross-country evidence from West Africa links CSA adoption to improved household food security (Tabe-Ojong et al., 2023), while studies in Ethiopia (Enyew & Gobie, 2025; Mwalupaso et al., 2025; Affoh et al., 2024), Nigeria (Omotoso & Omotayo, 2025), Sri Lanka (Cordell et al., 2021) and Punjab, India (Thakur et al., 2024) similarly find positive associations between CSA practice adoption and household food security or dietary diversity, with one study explicitly linking CSA practices to household dietary diversity outcomes among smallholders (Santalucia & Sibhatu, 2024).

Income and welfare effects are documented alongside productivity gains. Soil-conservation adoption is linked to higher smallholder incomes in South Africa's Qamata irrigation scheme (Ighodaro et al., 2020), while non-farm employment and welfare gains associated with CSA adoption and its scaling potential are examined in Ethiopia (Yitbarek & Tesfaye, 2022). At the same time, several studies caution that benefits are not universally or evenly distributed: wealth-related inequalities shape which households can adopt higher-cost practices such as drought-tolerant maize and conservation agriculture in Zimbabwe (Makate et al., 2019) and gender-differentiated welfare effects are documented in Nigeria (Daudu et al., 2025).

Resilience and risk-reduction outcomes are assessed through both perception-based and outcome-based measures. CSA innovations are associated with enhanced climate resilience among smallholders in the Blue Nile highlands of Ethiopia (Teklu et al., 2023), while studies of drought and water scarcity mitigation in Zimbabwe (Mpala & Simatele, 2023) and of agricultural drought risk and local adaptation in Thailand's Upper Mun River basin (Babel et al., 2024) link specific practices to measurable reductions in production risk. A systematic review focused on Ethiopia synthesises this risk-reduction evidence across multiple CSA practices (Tadesse & Ahmed, 2023).

Table 7. Outcome domains associated with CSA adoption

Outcome domain	Direction of reported effect	Representative studies
Productivity / yield	Generally positive, magnitude varies by practice and context	(Andati et al., 2023); (Mustafa et al., 2024); (Bibi, 2025); (Imran et al., 2018); (Komarek et al., 2019)
Food security & diet	Generally positive association with adoption	(Tabe-Ojong et al., 2023); (Enyew & Gobie, 2025); (Mwalupaso et al., 2025); (Affoh et al., 2024); (Omotoso & Omotayo, 2025); (Cordell et al., 2021); (Thakur et al., 2024); (Santalucia & Sibhatu, 2024)
Income & welfare	Positive but unevenly distributed across wealth groups	(Ighodaro et al., 2020); (Yitbarek & Tesfaye, 2022); (Makate et al., 2019); (Daudu et al., 2025)
Resilience & risk reduction	Positive; reduces exposure to drought and water scarcity	(Teklu et al., 2023); (Mpala & Simatele, 2023); (Babel et al., 2024); (Tadesse & Ahmed, 2023)

4.6. Methodological approaches used to study adoption behaviour

Methodologically, the corpus is dominated by quantitative, cross-sectional household-survey designs analysed with discrete-choice econometric models. Binary and multivariate probit and logit models are the most common estimation strategy, used to capture correlated adoption decisions across multiple, non-mutually-exclusive CSA practices, as in studies from Ethiopia (Zeleke et al., 2024), Ghana (Antwi-Agyei et al., 2021a) and Vietnam (Tran et al., 2020; Duc Truong et al., 2022). Ordered and multinomial models are used where adoption intensity, rather than a simple binary decision, is the outcome of interest, as in studies of adoption intensity among Nepalese rice producers (Upendram et al., 2023) and Ugandan coffee farmers (Kirungi et al., 2025).

Stated-preference methods - including discrete choice experiments, conjoint analysis and willingness-to-pay elicitation - represent a smaller but methodologically distinct sub-tradition, used to quantify smallholder preferences for incentivised CSA in Malawi (Schaafsma et al., 2019), farmer preferences and willingness to pay in Assam, India (Barman & Neog, 2024; Yadav et al., 2025) and expert and farmer preferences for CSA attributes among Kenyan potato producers (Ogola & Ouko, 2021).

Perception- and psychometric-based approaches, often complementing econometric models, draw on farmers' subjective risk perceptions, attitudes and self-efficacy beliefs, as illustrated by Nordic typologies of climate-risk response (Käyhkö, 2019) and by behavioural-driver analyses of Central American farmers' technology acceptance (Rodríguez-Barillas et al., 2024a; Rodríguez-Barillas et al., 2024b).

Life-cycle assessment and biophysical-economic modelling approaches, while less common, are used to evaluate the environmental sustainability trade-offs of CSA options at farm and crop-system levels (Acosta-Alba et al., 2019) and to prioritise land-use options at regional scale using linked biophysical-economic models (Shirsath et al., 2017). Qualitative and participatory methods - including role-playing games, mixed-content policy-document analysis and co-design workshops - are used to capture social learning and institutional mainstreaming processes that purely quantitative adoption models cannot access (Salvini et al., 2016; Diko et al., 2021; Andrieu et al., 2019).

This methodological landscape indicates a field still anchored predominantly in cross-sectional, self-reported adoption data, with comparatively few longitudinal panels, randomised or quasi-experimental impact evaluations, or remote-sensing-validated outcome measures - a gap discussed further below.

Table 8. Methodological approaches used to study CSA adoption behaviour

Methodological approach	Typical application	Representative studies
Binary / multivariate probit & logit models	Modelling correlated adoption decisions across multiple practices	(Zeleke et al., 2024); (Antwi-Agyei et al., 2021a); (Tran et al., 2020); (Duc Truong et al., 2022)
Ordered / multinomial models	Modelling adoption intensity rather than a binary decision	(Upendram et al., 2023); (Kirungi et al., 2025)
Stated-preference methods (DCE, conjoint, WTP)	Quantifying preferences for incentivised or attribute-specific CSA options	(Schaafsma et al., 2019); (Barman & Neog, 2024); (Yadav et al., 2025); (Ogola & Ouko, 2021)
Perception / psychometric approaches	Capturing risk perception, attitudes and behavioural drivers	(Käyhkö, 2019); (Rodríguez-Barillas et al., 2024a); (Rodríguez-Barillas et al., 2024b)
Life-cycle & biophysical-economic modelling	Evaluating environmental trade-offs and regional land-use prioritisation	(Acosta-Alba et al., 2019); (Shirsath et al., 2017)

Qualitative & participatory methods	Capturing social learning and institutional mainstreaming processes	(Salvini et al., 2016); (Diko et al., 2021); (Andrieu et al., 2019)

4.7. Regional and contextual patterns

Consistent with the country-level bibliometric results reported above, the substantive findings synthesised in this section are geographically concentrated. Sub-Saharan Africa - particularly Kenya, Ethiopia, Ghana, South Africa, Malawi, Zimbabwe and Tanzania - contributes the largest share of farmer-level adoption and impact studies, reflecting both the acute climate exposure of rain-fed smallholder systems in the region and the concentration of CGIAR and donor-funded CSA programming there. South and Southeast Asia - notably India, Pakistan, Bangladesh, Nepal and Vietnam - form a second major cluster, with a distinct emphasis on rice- and wheat-based systems, flood and drought risk and, in the Indian context, extension-education-oriented studies published in specialised journals such as the Indian Journal of Extension Education.

Research from high-income contexts - the United States (particularly California), the Netherlands and parts of Europe - is comparatively smaller in volume but methodologically distinct, often focusing on technical-assistance providers, farm-typology-based resilience assessment and regulatory frameworks for practices such as soil carbon sequestration (Verschuuren, 2018; Reidsma et al., 2015; Johnson et al., 2023b). Latin America, the Middle East and Central Asia remain comparatively under-represented, with individual studies from Peru (Aguilar-Luis et al., 2024), Costa Rica and other Latin American climate-smart villages (Acosta et al., 2021) and Syria (Alhaiek et al., 2025) illustrating important but still isolated contributions from these regions.

Table 9. Distinctive regional research emphases in the corpus

Region	Distinctive research emphasis	Representative studies
Sub-Saharan Africa	Farmer-level adoption and impact studies tied to CGIAR/donor-funded CSA programming	(Waaswa et al., 2024); (Dougill et al., 2021)
South & Southeast Asia	Rice- and wheat-based systems, flood/drought risk, extension-education framing	(Tran et al., 2020); (Duc Truong et al., 2022)
High-income contexts (US, Netherlands, Europe)	Technical-assistance providers, farm typologies, regulatory frameworks (e.g., soil carbon)	(Verschuuren, 2018); (Reidsma et al., 2015); (Johnson et al., 2023b)
Latin America	Isolated but methodologically rich contributions on agrobiodiversity and gendered access	(Aguilar-Luis et al., 2024); (Acosta et al., 2021)
Middle East	Emerging, conflict-affected-context research on perceptions and CSA potential	(Alhaiek et al., 2025)

5. DISCUSSION

The bibliometric and thematic findings reported above jointly depict a rapidly growing but still maturing field. Three points of convergence and three gaps merit particular attention.

First, there is strong convergence across highly diverse geographic and crop contexts on a common core of adoption determinants: extension access, education, credit, land tenure security, group membership and prior experience of climate risk. This convergence, visible both in the VOSviewer keyword network - where "adoption," "smallholder," and "adaptive capacity" cluster tightly together - and in the narrative synthesis, suggests that despite methodological heterogeneity, the underlying behavioural drivers of CSA adoption are relatively stable across contexts. This is encouraging for policy transferability: interventions strengthening extension delivery, input credit and farmer-group formation are likely to raise adoption regardless of the specific CSA practice or country in question (Waaswa et al., 2024; Kangogo et al., 2021; Ouédraogo et al., 2019).

Second, the literature converges on the conclusion that CSA adoption is not gender-neutral and that women farmers face compounding constraints in access to land, credit, extension and labour that are rarely fully addressed by generic CSA promotion strategies (Murray et al., 2016; Nchanji et al., 2023; Daudu et al., 2025). This suggests that gender-differentiated programme design, rather than gender as a post-hoc control variable, should be a standard feature of both future research and CSA extension practice.

Third, impact studies converge in finding generally positive but heterogeneous productivity, income and food-security effects of CSA adoption, with benefits systematically smaller or absent for poorer, land-constrained, or credit-constrained households (Makate et al., 2019; Daudu et al., 2025). This heterogeneity implies that average treatment effects reported in many studies may understate the targeting challenge facing CSA scale-up programmes aimed at the most vulnerable farmers.

Turning to gaps, a first methodological limitation is the corpus's heavy reliance on cross-sectional, self-reported adoption and outcome data analysed with probit- and logit-family models. While well suited to identifying correlates of adoption, these designs are poorly suited to establishing causal impact, are vulnerable to recall and social-desirability bias and cannot capture dis-adoption or the dynamic, path-dependent character of technology bundles over time (Hermans et al., 2021; Rodríguez-Barillas et al., 2024a). Longitudinal panel data, randomised or quasi-experimental impact evaluations and remote-sensing- or yield-trial-validated outcome measures remain comparatively rare in this literature and represent a priority for future research.

A second gap is geographic: the corpus's concentration in Sub-Saharan Africa and South/Southeast Asia, while understandable given climate exposure and donor programming, leaves Latin America, the Middle East and North Africa and Central and East Asia (outside China) comparatively thinly studied. Because this review's eligibility criteria required open-access publication in English-language journals, this concentration may partly reflect open-access publishing patterns and language of scholarship rather than the true geographic distribution of CSA research activity; subscription-access and non-English literature from these regions may fill some of this apparent gap.

A third gap is conceptual: several studies in the corpus explicitly critique the binary "adopt/non-adopt" framing that still dominates much of the literature, arguing that it obscures partial adoption, contextual modification and farmers' own rationales for rejecting recommended practices (Hermans et al., 2021; Vernooij et al., 2024). Greater conceptual and methodological attention to adoption as a continuous, dynamic and socially embedded process - rather than a one-off binary choice - would better reflect the on-the-ground behaviour these studies describe.

Finally, the strong thematic linkage between "climate-smart agriculture" and "climate change" in both the keyword network and the narrative synthesis confirms that, within this literature, CSA functions primarily as an operational vehicle for climate adaptation at the farm level rather than as a distinct paradigm competing with, for example, agroecology or conventional intensification. Future research explicitly comparing CSA outcomes against these alternative framings would help clarify CSA's comparative advantage as a policy instrument.

6. CONCLUSION

This review combined a bibliometric mapping of 138 open-access, peer-reviewed journal articles published between 2015 and 2025 with a thematic synthesis of their substantive findings on farmer adaptation to climate change through climate-smart agriculture. The bibliometric analysis shows a field that has grown rapidly since 2021, is published predominantly in multidisciplinary sustainability and food-systems journals and is empirically anchored in Sub-Saharan Africa and South/Southeast Asia, with the United States, Kenya, India and Ethiopia as the leading contributing countries. Keyword co-occurrence and thematic-map analysis confirm that adoption, smallholder livelihoods, food security and adaptive management are the dominant organising concepts linking climate-smart agriculture to climate change in this literature.

The thematic synthesis shows consistent findings across contexts regarding the socio-economic and institutional determinants of adoption (extension access, credit, land tenure, social capital and risk perception), the persistence of gendered constraints on access and benefit, the multidimensional nature of adoption barriers, the wide and evolving portfolio of practices studied and generally positive but unevenly distributed impacts on productivity, income and food security. Methodologically, the field remains dominated by cross-sectional survey designs and discrete-choice econometric models, with comparatively limited use of longitudinal, experimental, or remote-sensing-validated approaches.

For research, priorities include longitudinal and quasi-experimental impact evaluation, expanded geographic coverage beyond the current African and Asian concentration and more nuanced, non-binary conceptualisations of adoption as a dynamic process. For policy and extension practice, the consistency of adoption determinants across contexts suggests that investment in extension services, credit access, land tenure security and farmer-group formation - designed with explicit attention to gender and wealth differentiation - offers a robust, broadly transferable pathway to accelerating climate-resilient agricultural transitions among smallholder farmers.

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