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Mapping climate smart agricultural interventions in rice cultivation: a lexicometric and systematic review of methane emissions and yield outcomes

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Introduction: Climate Smart Agriculture (CSA) is a strategic framework designed to achieve productivity, resilience, and mitigation simultaneously. In rice cultivation, major CSA interventions are increasingly studied but evidence remains fragmented. This review consolidates global findings to clarify adoption drivers, intervention effectiveness, and thematic evolution.

Methods: A systematic literature review was conducted following PRISMA guidelines. Sixty-one peer-reviewed articles (2015–2025) from Scopus and Web of Science were analyzed. Bibliometric mapping, lexicometric analysis, and the PICO framework structured the synthesis. Tools including Biblioshiny, CiteSpace, VOS Viewer, and IRaMuTeQ were used to examine collaboration networks, discourse clusters, and intervention outcomes.

Results: The review identified consistent evidence of CSA's potential to reduce methane emissions and enhance rice yields. Bundled interventions demonstrated stronger performance than single practices. Socioeconomic and demographic factors such as education, credit, and extension services were found to significantly influence adoption. Lexicometric analysis revealed convergence of discourse around sustainability, resilience, and innovation. Bibliometric mapping highlighted rapid growth of CSA-rice research, strong international collaboration, and concentration within key journals and author clusters.

Discussion and conclusion: CSA in rice cultivation delivers measurable triple-win outcomes but adoption remains uneven due to socio-institutional barriers. Policy frameworks integrating technical, financial, and social mechanisms are essential for scaling. Future research should prioritize comparative trials across regions, inclusion of demographic variables, and equity considerations to strengthen generalizability and guide targeted investments.

KEYWORDS
climate-smart agriculture, greenhouse gas mitigation, methane emissions, rice cultivation, yield outcomes

1 Introduction

Global warming is the main cause of climate change, which has immense impact on the biological, physical, and human systems (Nelson and Kokic, 2004; McSweeney et al., 2010). In most developing countries, climate change influences agricultural productivity due to the fluctuating weather conditions, including floods and droughts, collapse of ecological food webs and financial resources (Niang et al., 2014; Vermeulen et al., 2013). It has been highlighted by the Intergovernmental Panel on Climate Change (IPCC) that climate change affects the food and livelihood security at the global level. Damages caused by extreme weather serve as dependable indicators of climate change's adverse effects (Patt et al., 2010). The impact of climate change on agriculture is severe (Jayadas and Ambujam, 2021; Long et al., 2016; Mugambiwa and Makhubele, 2021) as the projections indicate a 50% drop in rain-fed crop yields and complete crop failure if global temperatures exceed 1.5 °C (Nkemelang et al., 2018; Schleussner et al., 2016). These problems are even worsened when the world is projected to increase food demand. The publicity on climate change has not yet been given as much weight as other socioeconomic issues despite such worrying trends (Capstick et al., 2015). The convergence of these challenges poses a significant threat to global agriculture under climate change, demanding innovative and sustainable strategies to safeguard food security (Barooah et al., 2023). Agriculture is believed to be as a serious source of greenhouse gas emissions, the rice production subsector adding up to 46.3 percent (FAO, 2010).

Rice serve as a staple food for half the world's population. It is estimated that over 3 billion individuals globally consume rice daily (Emmanuel et al., 2024; Hashim et al., 2024). There is a need to be at least 25% more production of rice by 2030 to meet the global population growth and demand (Seck et al., 2012). But the sustainability of rice production has been questioned because of the problems with soil erosion, water pollution, and the lack of water supply (Bouman et al., 2007; Nelson et al., 2009). High temperatures slow rice growth and development because they increase evapotranspiration, which lowers soil and plant moisture availability (Ren et al., 2023). Unstable rainfall raises the likelihood of rice crop failure across time scales (Zhang et al., 2023).

During the conference on food security during 2010 at Hague, FAO pioneered the framework of Climate Smart Agriculture (CSA) as a solution to these strenuous problems (RAO et al., 2024; Rao, 2017; Vetri Selvi et al., 2025), particularly to underdeveloped countries (Long et al., 2016; Ahmad et al., 2020; Vetri Selvi et al., 2025). Given the climate change, the concept of CSA emerged as an effective tool of feeding the growing population of the world (Mccarthy and Branca, 2011). FAO describes CSA integrates three key targets "Sustainable agriculture raises resilience, increases productivity, lowers greenhouse gas emissions, and helps achieve national development and food security goals (FAO, 2010). The implementation of climate change adaptation measures, including the application of climate-smart agriculture (CSA) methods, may enhance food security, economic benefits, and efficiency of production (Khatri-Chhetri et al., 2017; Tam and Shimada, 2019). Climate-smart agriculture practices (CSAP) are a holistic approach to sustainable farming where the core aim is to mitigate the problem of climate change and avert the environmental sustainability and food security (Begna Wakweya, 2022).

CSA addresses food insecurity and global warming simultaneously and approaches the concept of sustainable development. To realize sustainable agricultural development that will result in food security, this strategy aims at giving the required technological, policy and investment conditions (Harahap et al., 2022). To boost agricultural production and generate income, the CSA integrates conventional and innovative methods to improve livelihoods, strengthen food security, and foster development. It also seeks to enhance resilience across scales from individual farms to national systems while mitigating climate impacts by reducing greenhouse gas emissions and promoting carbon sequestration (Campbell et al., 2014).

Despite the growing body of literature on climate-smart agriculture (CSA) and its relevance to food security, several critical knowledge gaps persist that justify the need for a focused systematic review. First, while CSA has been broadly conceptualised as a framework for sustainable food production, empirical evidence specifically examining the effectiveness of CSA practices in rice cultivation particularly in simultaneously achieving methane emission reduction and yield enhancement remains fragmented and geographically inconsistent (Das et al., 2024; Omoyajowo et al., 2025). Most available studies are site-specific and context-dependent, limiting their generalisability across diverse rice-growing regions and agroecological zones (Gemtou et al., 2024). Second, despite extensive individual studies on practices such as alternate wetting and drying (AWD), biochar application, and system of rice intensification (SRI), no comprehensive synthesis has compared the simultaneous triple-win outcomes of CSA productivity, adaptation, and mitigation across different rice farming systems at a global scale (Chang et al., 2024). Third, the socioeconomic and demographic dimensions of CSA adoption in rice cultivation, including the influence of farm size, gender, education level, and land tenure on farmer decision-making, have been inadequately integrated into existing reviews (Gemtou et al., 2024). Finally, from a methodological standpoint, lexicometric analysis, a quantitative text-mining approach was used to identify dominant themes, conceptual clusters, and co-occurrence patterns within a body of CSA literature in rice production systems (Aria and Cuccurullo, 2017). The absence of such analysis means that the thematic structure, terminological trends, and conceptual evolution of CSA research in rice cultivation lack comprehensive mapping, leaving blind spots in our understanding of how the field has developed and where future research attention is most needed (Aria and Cuccurullo, 2017). These collective gaps underscore the need for a rigorous systematic literature review that consolidates and synthesises global empirical evidence on CSA practices in rice production systems, providing a holistic understanding of what works, where, and for whom, in order to inform targeted policy, investment, and future research priorities.

The current research situation regarding the topic of climate smart agriculture is comprehensively investigated in this systematic literature review, synthesizing empirical information among 61 peer reviewed articles retrieved from the databases Scopus and Web of Science. The paper is expected to provide answers to four key research questions namely.

> *RQ1:* What demographic and socioeconomic characteristics of rice-farming populations including farm size, gender, land tenure, and education level most significantly determine the adoption of climate-smart agriculture practices for methane mitigation and yield enhancement?
>
> *RQ2:* How do specific CSA interventions compare in their effectiveness for simultaneously reducing methane emissions and improving rice yield under varying agroecological and climatic conditions?

> *RQ3:* To what extent do bundled CSA interventions outperform conventional rice farming systems in terms of resource-use efficiency, climate resilience, and greenhouse gas reduction, particularly in climate-vulnerable smallholder contexts?
>
> *RQ4:* What role do discourse convergence around sustainability, resilience, and innovation as identified through lexicometric analysis play in shaping the thematic evolution of climate-smart agriculture research in rice systems?

With the help of the bibliometric analysis, PICO framework, and lexicometric analysis, this review synthesizes global evidence on CSA in rice cultivation. It first maps research trends and collaboration networks through bibliometric techniques. Next, the PICO framework structures the evidence base by examining farmer populations, CSA interventions, comparisons with conventional practices, and outcomes such as yield gains and methane reduction. Lexicometric analysis then identifies dominant discourse clusters and thematic convergence around sustainability, resilience, and innovation. The synthesis evaluates interventions like alternate wetting and drying (AWD), biochar application, and system of rice intensification (SRI), while also highlighting socioeconomic drivers of adoption such as credit, education, and extension services. Finally, the review discusses climate smart agricultural interventions and its outcome, while pointing to critical gaps and future research directions.

2 Methodology

The research involved a Systematic Literature Review (SLR) to identify, critically analyse and synthesize peer-reviewed research dealing with carbon credit in agriculture. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were used to conduct the review, where transparency, rigor and reproducibility were ensured in the identification of literature, screening, eligibility evaluation, and synthesis processes. The compliance with PRISMA standards helped to select the relevant studies systematically and objectively and improve the methodological soundness of the review by properly describing the inclusion and exclusion criteria, data collection procedures and synthesis strategies (Page et al., 2021).

2.1 Search strategy

A comprehensive search was conducted in Scopus & Web of Science databases with the following search strings: "Climate smart agriculture" OR "Climate smart farming" OR "climate resilient agriculture" OR "Methane reduction*" OR "Climate friendly agriculture*" OR "Regenerative agriculture*" AND "Paddy" OR "Rice" in July 10 2025. The search parameters used in both databases were article title, abstract, key words.

2.2 Inclusion and exclusion criteria using PRISMA

The PRISMA flow chart (Figure 1) shows the number of articles included and excluded in each step. The initial search resulted in 205 articles from Scopus and 205 articles from Web of Science. The following filters were applied in both databases: articles and English language, which resulted in 72 documents from Scopus and 99 documents from Web of Science. The extracted documents from the databases were merged in R Studio and duplicates were removed ($n = 54$). The final list of articles ($n = 171$) underwent a quality assessment in a two-stage screening. At the first stage, screening was done based on the title and abstract. The articles relevant to climate-smart agriculture were selected. In the second stage, a full-text screening was done by analysing the whole content based on its relevance to the scope and objectives of the study. The exclusion criteria applied in this selection process involved articles focused on chemical aspects; additional medicinal crops, and do not specifically work on methane emission were excluded based on the defined screening criteria and only 61 articles have met the review requirements.

2.3 Data analysis

The study utilized RStudio, Biblioshiny, Citespace, VOS Viewer and IRaMuTeQ for the quantitative data analysis and the visualization of results. This review also integrates bibliometric analysis (Aria and Cuccurullo, 2017). It introduces the growth and development in the research field, the new trends, themes and collaboration networks between the authors and the countries. Lexicometric analysis was used to examine the textual patterns within the selected CSA literature. It identified frequently occurring terms, semantic clusters, and framing trends that complement the PICO-based synthesis, offering deeper insight into how climate-smart practices are discussed across disciplines and regions. PICO framework (Population, Intervention, Comparison, Outcome) provides a structured lens to formulate research questions and categorize evidence. It guides the synthesis of CSA interventions (e.g., water-saving technologies, nutrient management) and their outcomes (e.g., yield, resilience) for rice-growing populations. By integrating these methodologies, the research aims to map existing evidence, assess intervention effectiveness, and highlight the positive impacts of CSA such as improved yield performance and reduced methane emissions within rice-based systems. It presents a dual emphasis on environmental sustainability and agricultural productivity within rice cultivation, examining the potential of CSA practices to address both climate mitigation and yield enhancement.

2.4 Validity of the textual corpus in lexicometric approach

The corpus comprises 61 peer-reviewed articles (2015–2025) with a systematic selection strategy (via PRISMA protocol) on Scopus and Web of Science. The thematic coherence (all the studies consider CSA interventions in rice systems), source credibility (peer-reviewed empirical research) and adequate lexical density (20,078-word occurrences; 460 active forms) determine its validity and allow statistically reliable segmentation. The lexicometric analysis (IRaMuTeQ) was chosen due to the research question aiming to define discourse convergence concerning sustainability, resilience, and innovation. It uses thematic classes which are derived inductively through word co-occurrence patterns unlike manual coding strategies (e.g., NVivo) and minimizes interpretive bias. It offers deterministic clustering and clear class formation as compared to topic modelling. This strategy, along with bibliometric mapping, allows developing a strong description of how discursive structures influence thematic progression of CSA work in rice systems.

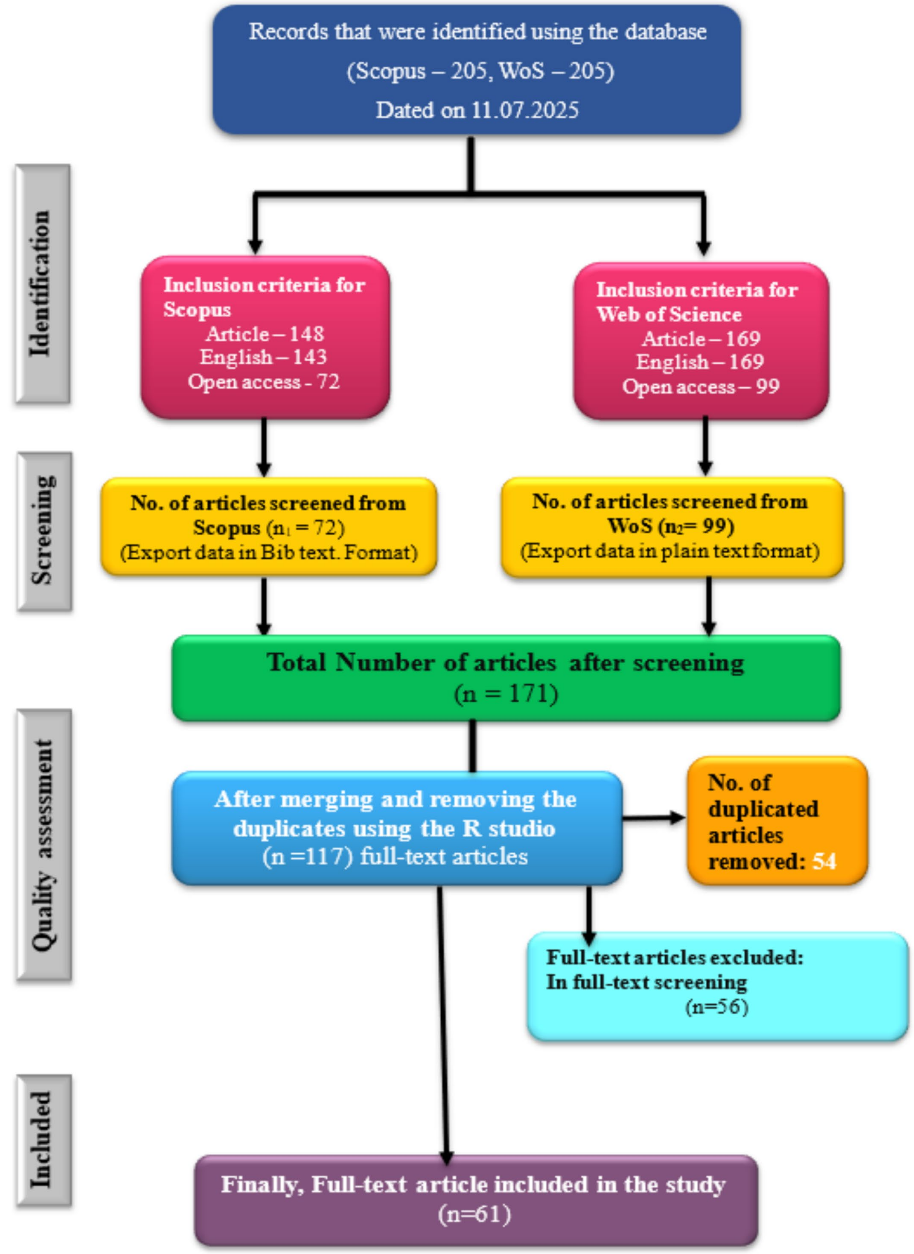


FIGURE 1
PRISMA framework source: authors' compilation (2025).

The approach (IRaMuTeQ) has been chosen due to procedural convenience, but because the research question is methodologically oriented, aiming to study the convergence of discourse around sustainability, resilience and innovation. Lexicometric analysis derives classes of themes inductively based on patterns of word co-occurrence, unlike software like NVivo or ATLAS.ti, which need researcher-created schemes of coding and can cause interpretive pre-structuring. This specifically suits the observation of latent discursive convergence without any pre-defined categories that might prejudice the application of thematic development. IRaMuTeQ provides deterministic hierarchical clustering and factorial correspondence analysis provide mutually exclusive statistically justified classes, and thus, increase transparency and reproducibility in a systematic review setting, as compared to probabilistic topic modelling (e.g., LDA). Such similarity analysis and correspondence mapping further facilitate the determination of conceptual proximity and dominance in the corpus, which directly aids in studying the interactions and embedding of the discourse of sustainability, resilience, and innovation.

3 Results and discussions

3.1 Bibliometric analysis

3.1.1 An overview

The Figure 2 presents the core bibliometric profile of the dataset, encompassing 117 documents drawn from 71 sources over the timespan 2015–2025. The annual growth rate of 21.48% signals a field in rapid and sustained expansion, reflecting the intensifying global urgency around climate adaptation in agricultural systems, particularly rice-based farming, and suggesting that scholarly interest in CSA-rice research has been continuously accelerating rather than representing a short-lived trend, likely driven by escalating climate risks, international policy commitments, and increasing funding directed toward food system resilience. The dataset includes 534 authors, with only 3 single-authored documents, indicating that collaborative, multi-author research is the dominant mode of scholarly production, further reinforced by the international co-authorship rate of 52.14% and an average of 5.71 co-authors per document, both of which point to strong cross-border research partnerships consistent with the transboundary nature of climate challenges in rice-producing regions. The average document age of 3.16 years confirms that the corpus is recent and methodologically current, while the average citation counts of 20.34 per document clarified here as citations per document rather than per year reflect a moderately high scholarly impact, suggesting that CSA-rice publications are actively engaged with and built upon by subsequent researchers. The 421 Author Keywords underscore the thematic breadth and conceptual diversity of CSA-rice scholarship, spanning agronomy, ecology, climate science, food security, and policy, a richness that the subsequent keyword co-occurrence and thematic analyses further explore. Finally, zero (0) references do not imply an absence of citations but the database or analysis tool like Biblioshiny, may not have extracted the reference data. While the broad overview provides the scope and importance of literature, the analysis of annual publication trends helps to understand the changes in literature over time.

3.1.2 Annual scientific production

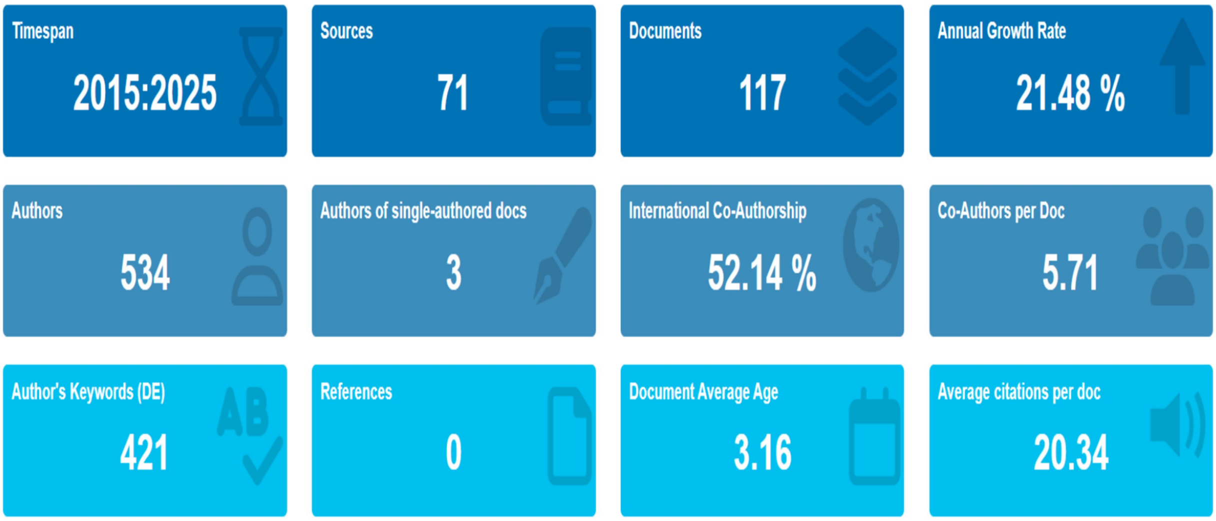
The graph in Figure 3 shows a clear and accelerating growth in annual scientific production on Climate-Smart Agriculture (CSA) in rice cultivation from 2016 to 2025. Publications remained minimal and relatively stagnant between 2016 and 2018, indicating that CSA rice research was still emerging as a specialized field. From 2019 onward, output increased steadily, reflecting heightened global attention to methane mitigation, sustainable intensification, and climate resilience in rice systems. The most pronounced surge occurred between 2022 and 2024, where publications rose sharply and peaked in 2024, demonstrating the consolidation of CSA as a central research and policy priority aligned with climate governance and SDG commitments. The slight decline observed in 2025 likely reflects incomplete indexing rather than a substantive reduction in research activity. Overall, the figure indicates a transition from exploratory research to a mature and rapidly expanding scientific domain with strong interdisciplinary and policy relevance.

3.1.3 Most influential journals

Among the most relevant sources in Figure 4 the highest contribution comes from Agronomy-Basel with nine documents, establishing it as the leading outlet in this research area. Close behind are Frontiers in Sustainable Food Systems and Sustainability, each with seven documents, reflecting their strong engagement with CSA scholarship. Mid-level contributors include Agriculture-Basel and Frontiers in Environmental Science, both with five documents, showing their focus on agronomic and environmental dimensions of CSA. Several other journals such as Agricultural Systems, Agriculture Ecosystems & Environment, Climate Risk Management, Environmental Challenges, and the Journal of Agriculture and Food Research each published three documents, indicating consistent but smaller contributions. Overall, the distribution demonstrates that CSA research in rice cultivation is concentrated in a few high-output journals, particularly those emphasizing agronomy, sustainability, and environmental science, while a broader set of outlets contributes smaller volumes. This pattern highlights both the interdisciplinary nature of CSA research and the growing interest across diverse domains such as food systems, climate risk, and ecological management.

3.1.4 Most influential authors

The graph of most relevant authors in Figure 5 highlights the scholars who have made the most substantial contributions to this field of climate-smart agriculture (CSA) research on rice systems, between 2015 and 2025. The leading contributors are Jat M, Jat H, and Sharma P, with thirteen, ten, and nine articles respectively,



Timespan 2015:2025
Sources 71
Documents 117
Annual Growth Rate 21.48 %
Authors 534
Authors of single-authored docs 3
International Co-Authorship 52.14 %
Co-Authors per Doc 5.71
Author's Keywords (DE) 421
References 0
Document Average Age 3.16
Average citations per doc 20.34

FIGURE 2
A general overview of literature.

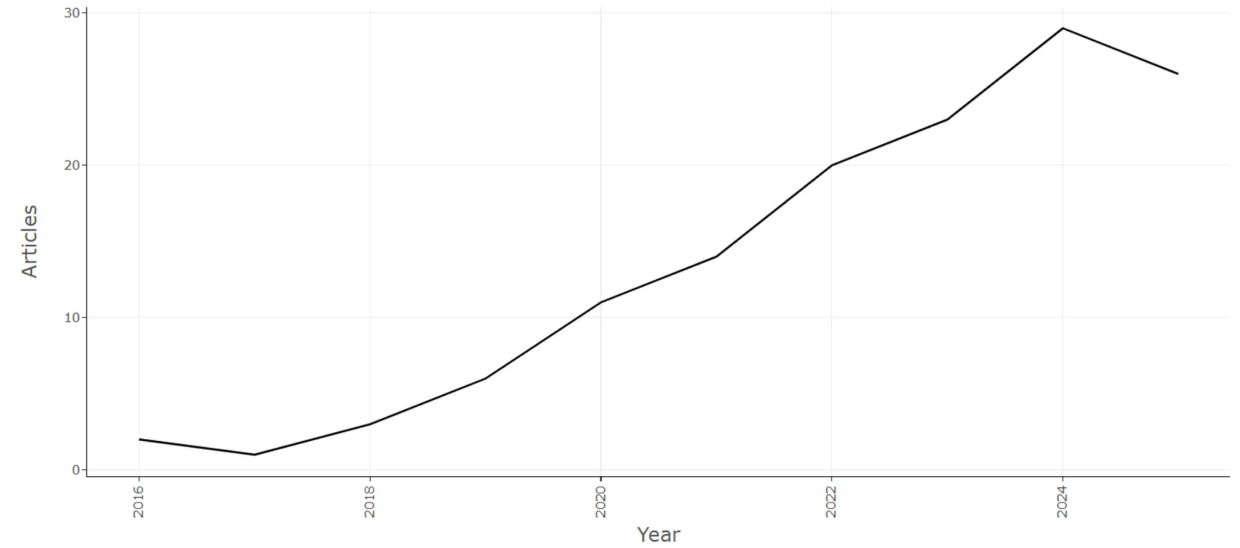


FIGURE 3
Annual scientific production.

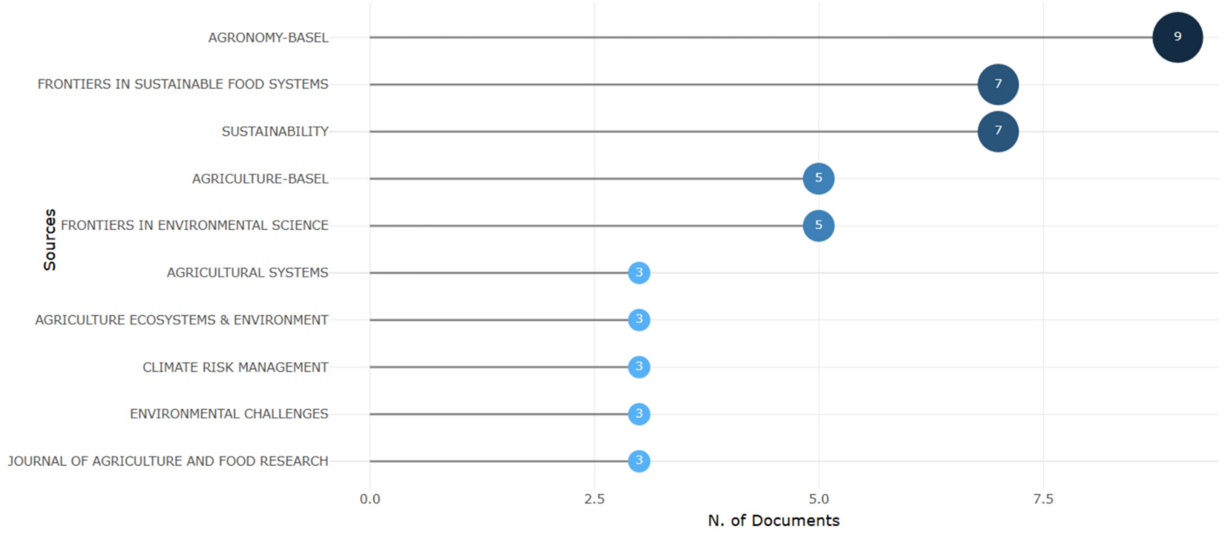


FIGURE 4
Most relevant journals.

indicating their central role in shaping CSA discourse and advancing interventions such as alternate wetting and drying and stress-tolerant varieties. Other notable contributors include Choudhary M and Krupnik T, each with seven publications, and Datta A, Kakraliya S, and McDonald A, with five articles each. This concentration of output among a relatively small group of prolific authors suggests the formation of strong research clusters or epistemic communities that drive knowledge production and influence policy framing in CSA–rice systems. Their repeated contributions also reflect continuity and specialization, ensuring that certain practices and themes particularly methane mitigation, resilience, and adoption dynamics remain at the forefront of scholarly and applied discussions. Overall, Figure 3 demonstrates that while CSA research is broadly interdisciplinary, a core group of authors has played a pivotal role in consolidating evidence and shaping the trajectory of rice-focused CSA scholarship.

3.2 Thematic analysis

3.2.1 Thematic map

Figure 6 represents the thematic map, climate-smart agriculture, climate change, and rice are the main motor themes (relevant and highly developed themes that drive and shape the core of the study area) implying that they play a big role in the direction and development of CSA-rice research. Themes such as methane, greenhouse gas emission, mitigation, management and conservation agriculture appear to be in the process of transition or emergence, moderately developed and increasingly more popular and prominent. Conversely, the niche themes are specialized yet less significant topics such as index insurance, risk management, and rural development, which have substantial internal development and less influence on the overall subject of study. Abiotic stress

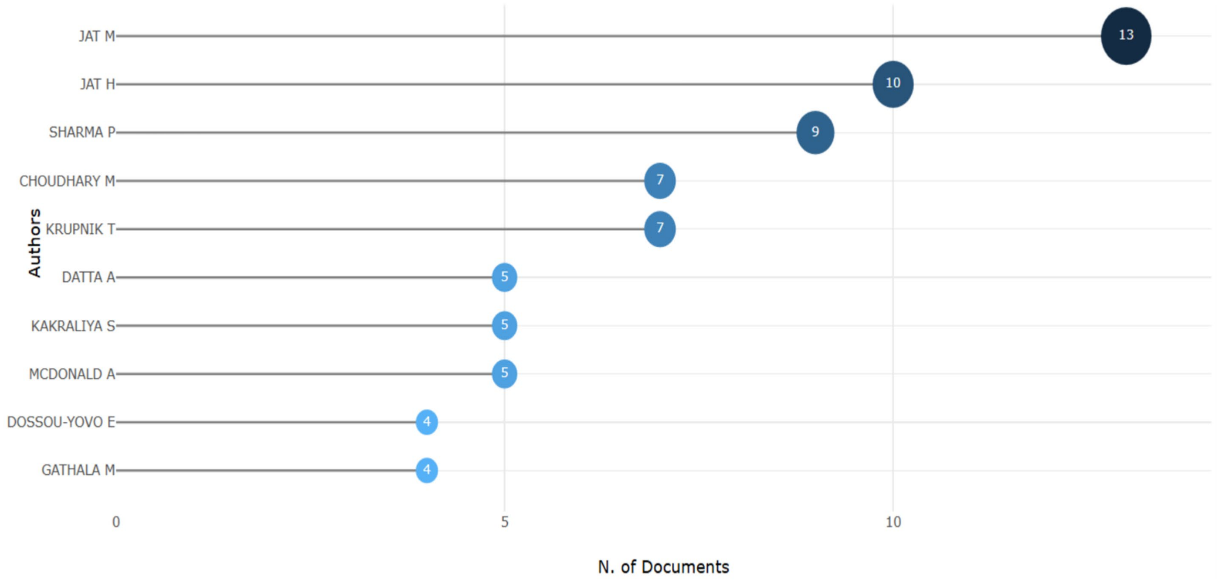


FIGURE 5
Most relevant authors.

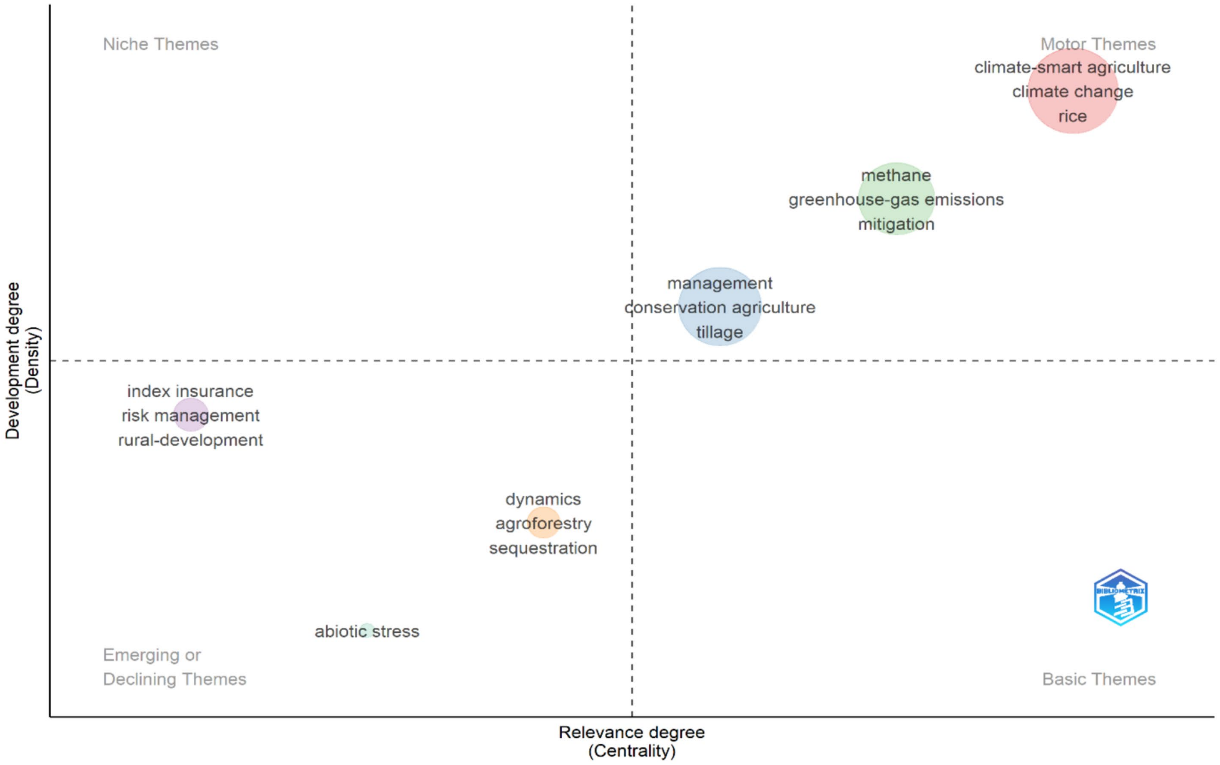


FIGURE 6
Keyword thematic map.

and other aspects of agroforestry, dynamics, and sequestration are other developing or declining topics that are noted in the lower-left quadrant. These themes are currently of little importance and have limited growth and can be gaining initial momentum or value of the study. Another quadrant, the lower-right one, reveals the core themes, the basic ideas that are vital to the matter, but not yet developed, which means that the areas require further consolidation. In general, the map demonstrates that a study landscape will be characterized by dominant CSA-rice themes, as the stress-related ecological themes will be either emergent or declining, the mitigation-related topics will be growing, and the specialty insurance-related themes will not enter the center stage.

3.2.2 Three field plot

The three field Plot in Figure 7 illustrates the percentage of the sources (SO) (left), keywords (DE) (right) and authors (AU) (center). It also determines the authors of whose work is in a given topic and in which journals it is published. The Sankey diagram illustrates the connection between the author, sources and the keywords and it shows that the connection lines are going to be thicker in case more linkages exist between the variables. Author Jat M. who worked on the keywords, Climate smart agriculture, Climate change mitigation, and adoption and published in the Journal of Frontiers in Sustainable Food Systems followed Dossou-yovo e has worked on the keywords “Climate smart agriculture”, “food security”, “rice”, “adoption” and then the author published most articles in the Journal of frontiers in sustainable Food systems. Sharma P, who works on the keywords “Climate smart agriculture,” “Climate change mitigation,” and has published his articles in the Agronomy-Basel and Agriculture Basel Journal.

3.3 Network analysis

This cluster has keywords such as climate change, climate-smart agriculture, investment appraisal, smallholder farmers, adaptation strategies, sustainable agriculture, rice farming, small farmers, climate change adaptation, regenerative agriculture management, soil perception, weather, environment, water, productivity, grain, and irrigation. The most recently used keywords are climate change and conservation agriculture. In Figure 8, the co-occurrence network map, every coloured node is presented in the form of an indicator in the network visualization. The size of each node ensures the most salient variable as it shows the repetition or frequency of indicators used in the many studies. The co-occurrence frequency of two labels is shown by the thickness of line connecting the nodes. Existing stronger relationships, or the rate of studies concerning the issue, are shown by nodes of similar colour. The biggest and the most central node is the keyword climate smart agriculture and followed by climate change. The areas, which have the most significant links to climate-smart agriculture, include rice, climate change adaptation, mitigation, greenhouse gas emissions, sustainable agriculture, food security, and conservation agriculture.

The timeline visualization map (Figure 9) displays the evolution of the research themes over time with the help of a few elements of the legend. Each numbered cluster on the right (e.g., 0 sustainable agriculture, 1 sub-Saharan Africa, 2 conventional methods) represents a large subject group, the lower the number, the larger the group. The length and persistence of each theme is represented in the length of the horizontal bar running out of the label pointing to the length of time a cluster has been functional over the period, 2016–2025. By placing nodes (small squares) along those bars that indicate significant articles or keywords cited, the user is able to follow when that specific idea assumed significance. The colors of the nodes reflect the year of popularity, purple for older years such as 2016 and red for more recent years such as 2025, which in turn represents how knowledge flows and the idea connections between themes over time. Although the keywords that are put along the timelines can provide a reflection of the main ideas that the various clusters are based upon, the color coloring of the clusters on the right helps to visualize the separation of the thematic groups. The legends taken, in whole, render the time history of the study landscape, thematic arrangement, and relation intelligible, so as to be able to discern both long-standing areas of concern and novel developments in the subject.

3.4 Critical interpretation of analysis

Beyond descriptive mapping, the bibliometric networks reveal structural dynamics that shape technological adoption and

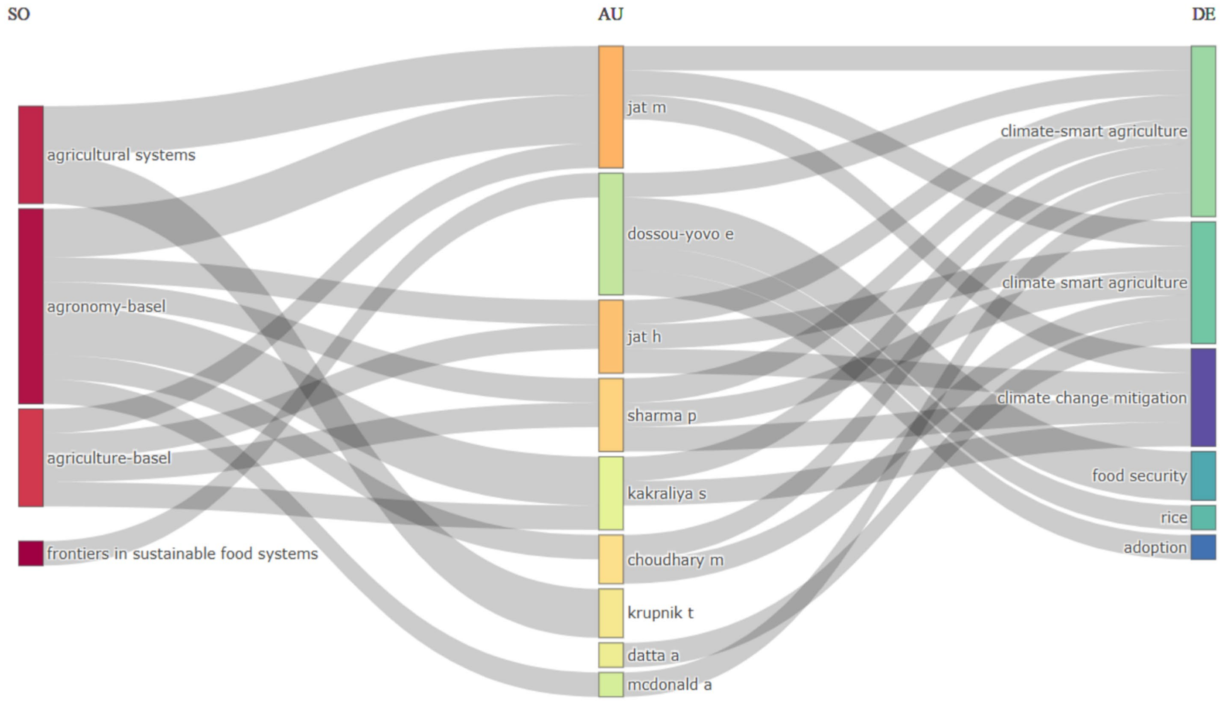


FIGURE 7
Three-field plot using R studio.

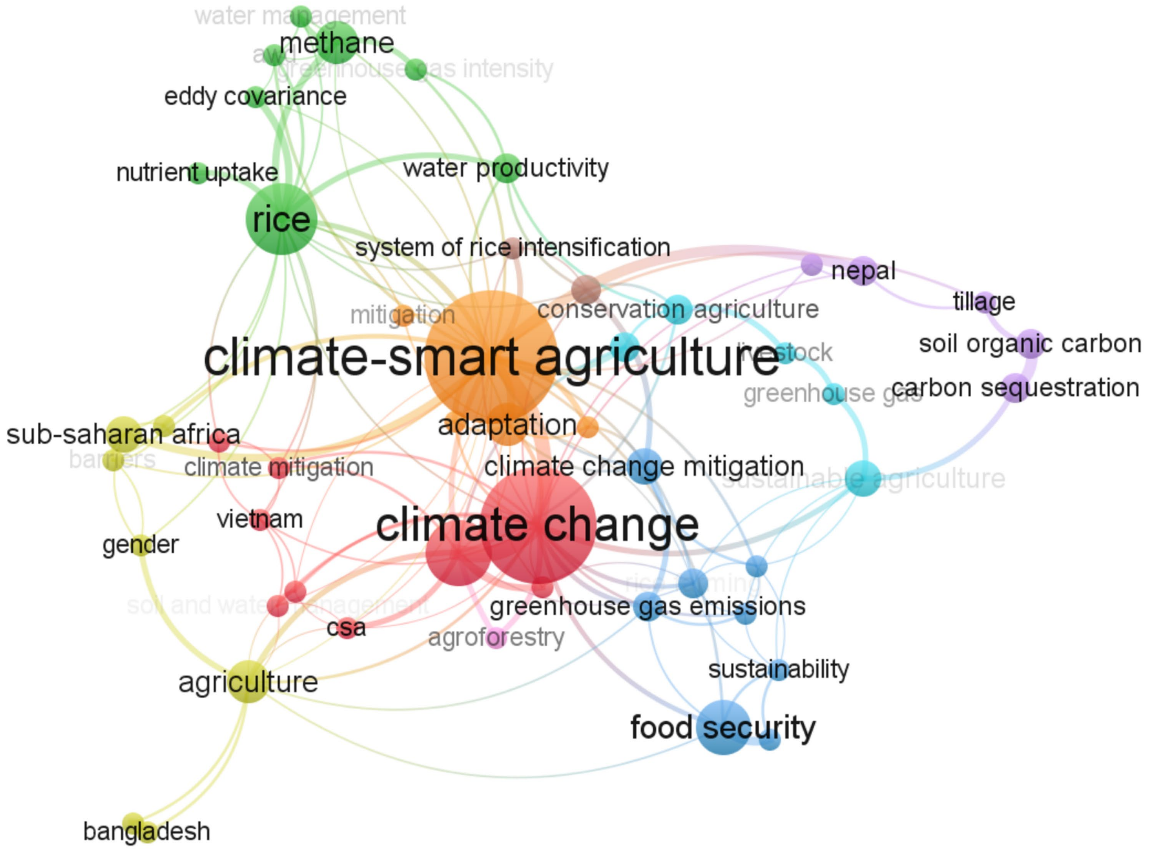


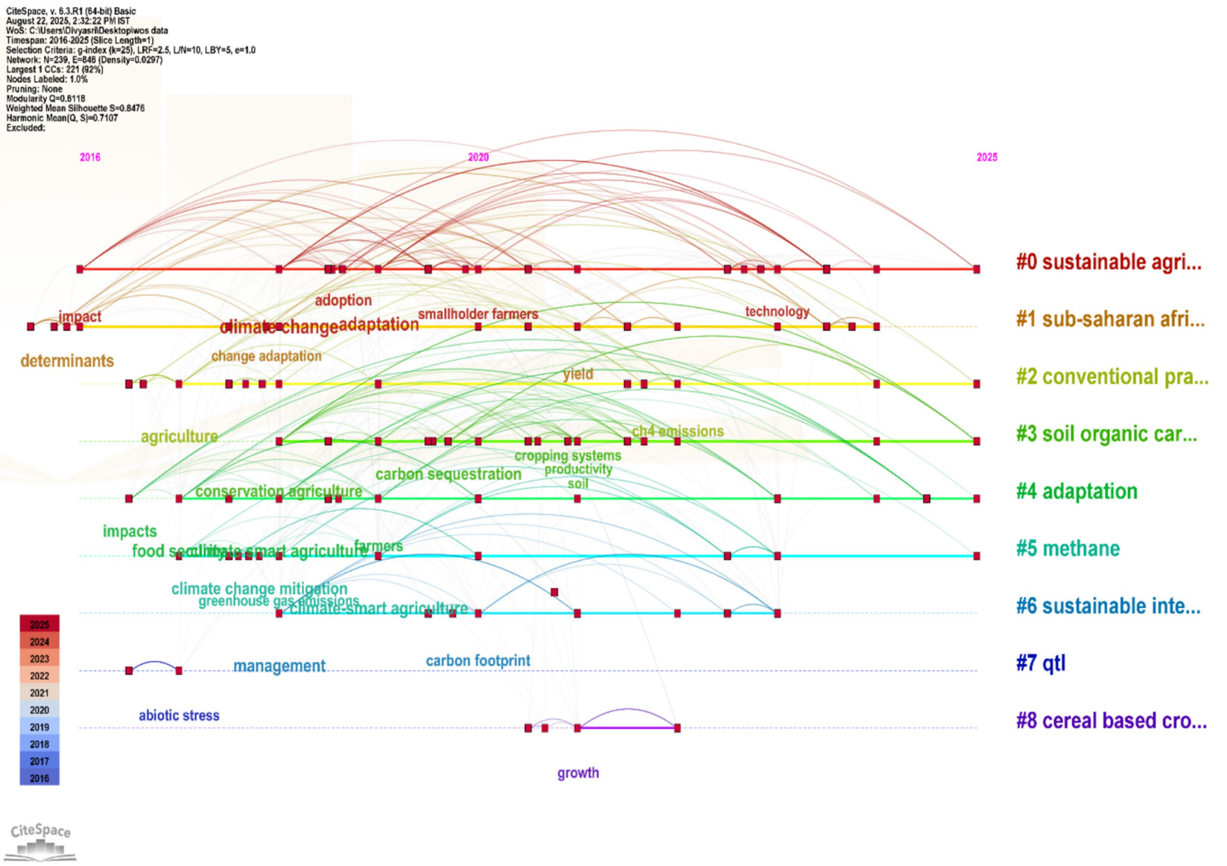
FIGURE 8
Co-occurrence network map of author keywords.

agricultural governance in CSA–rice systems. The concentration of publications within a limited number of journals and recurring author clusters suggests the emergence of epistemic communities that influence research framing and policy coordination (Manyike et al., 2025). According to research on adoption dynamics, innovations that are deeply embedded within dense and well-connected networks are more likely to diffuse across research, policy, and extension systems, thereby enhancing actual uptake on the ground (Erick et al., 2025). For example, AWD (Alternate Wetting and Drying) and stress-tolerant varieties are frequent targets of high-centrality research clusters, suggesting that their prioritization in funding and policy dialogues may be influenced by their strong bibliometric positioning (Manyike et al., 2025). In contrast, socio-institutional dimensions of adaptation such as gender-responsive extension or local governance arrangements remain more peripheral in bibliometric structures despite their importance for equitable adoption outcomes (Barooah et al., 2023).

Moreover, the clustering of policy-related keywords such as *investment*, *coordination*, and *institutional support* indicates that CSA adoption is not merely a technical choice but a governance-mediated process that relies on multi-stakeholder coordination and institutional incentives. This aligns with evidence that CSA adoption pathways are shaped by enabling environments, including extension systems, credit mechanisms, and cross-scale policy integration (Schleussner et al., 2016). Thus, bibliometric centrality reflects not only academic prominence, but also knowledge flows that influence policy narratives, funding priorities, and governance architectures that ultimately affect which CSA practices are adopted and scaled in rice systems (Jat et al., 2022).

At the governance level, CSA has been framed as a triple-win strategy integrating productivity, adaptation, and mitigation (Lipper et al., 2014). However, bibliometric clustering suggests that mitigation-oriented metrics, particularly methane quantification, receive disproportionate attention. This may reflect alignment with global climate reporting frameworks and international funding priorities, thereby influencing national agricultural policy agendas. Agricultural transformation under climate change is increasingly embedded within global environmental governance architectures, where research centrality can shape investment flows and institutional design (Campbell et al., 2014).

Moreover, the clustering of policy-related terms such as investment, extension, and coordination demonstrates that CSA adoption is governance-mediated rather than purely technological. Innovation systems literature emphasizes that adoption outcomes depend not only on technical efficiency but also on enabling institutional environments, financial incentives, and collective action mechanisms. Therefore, bibliometric centrality reflects consolidation of policy-relevant knowledge that shapes subsidy schemes, extension strategies, carbon credit mechanisms, and climate-smart village initiatives. By integrating bibliometric, lexicometric, and PICO-based findings, this review demonstrates that knowledge networks function as governance architectures. In doing so, these knowledge networks determine which technologies achieve scale, which narratives steer funding priorities, and which farmer groups gain institutional support, thereby shaping the overall trajectory of climate-smart agricultural transformation in rice systems.



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CiteSpace, v. 6.3.R1 (64-bit) Basic
August 22, 2025, 2:32:22 PM IST
WoS: C:\Users\Divyasri\Desktop\wos data
Timespan: 2016-2025 (Slice Length=1)
Selection Criteria: g-index (k=25), LRF=2.5, L/N=10, LBY=5, e=1.0
Network: N=239, E=846 (Density=0.0297)
Largest 1 CCs: 221 (92%)
Nodes Labeled: 1.0%
Pruning: None
Modularity Q=0.8118
Weighted Mean Silhouette S=0.8476
Harmonic Mean(Q, S)=0.7107
Excluded:
```

FIGURE 9
Time zone visualization map in CiteSpace.

4 Lexicometric analysis

> *RQ4:* What role do discourse convergence around sustainability, resilience, and innovation as identified through lexicometric analysis play in shaping the thematic evolution of climate-smart agriculture research in rice systems?

A lexicometric qualitative analysis, in conjunction with typical systematic literature review approaches, was used to get deeper insights into climate-adaptive agricultural practices in rice production. In 2009, a French researcher Pierre Ratinaud developed Lexicometric analysis that offers in-depth quantitative study of textual material and is implemented with the help of Iramuteq computer programmes (Abhayawansa, 2011). The lexicometric tools allow researchers to combine the qualitative and quantitative approaches (Shankar et al., 2022) and statistical analysis to identify crucial clusters within a concept. Moreover, not much can happen in terms of the human bias due to the lexicometric analysis using the automated textual analysis (Illia et al., 2014; Mandják et al., 2019). Consequently, it minimizes the likelihood of biases by the researcher, and provides in-depth understanding of the concepts within an area of study (Shankar et al., 2022).

4.1 Similarity analysis

Lexicometric analysis with Iramuteq separates text into segments and clusters through similarity analysis, where proximity and recurrence patterns depict conceptual linkages. The similarity network (Figure 10) highlights "knowledge" as the central theme connecting CSA discourse. Orange clusters link climate, adaptation, shock, and resilience, reflecting strategies for local response and system endurance. Purple and light blue emphasize knowledge flows, outreach, and stakeholder involvement, underscoring participatory governance and policy coherence. Green and turquoise highlight sustainability strategies, agroforestry, and land management. Yellow and olive represent system-level themes of food security, irrigation, and livelihoods. Light green focuses on institutional capacity, infrastructure, and evidence-based indicators. Purple-pink illustrates adoption, technology innovation, incentives, and digital agriculture. The large red cluster centers on productivity, diversification, and environmental quantification, especially methane mitigation in rice systems.

Overall, the visualization shows knowledge mobilization as the key mediator between science, policy, and practice. Segmentation reflects CSA's conceptualization across adaptation, mitigation, productivity, and farmer innovation. The clusters collectively highlight climate resilience, sustainability, livelihood enhancement, and governance, consistent with manual synthesis of CSA literature and reinforcing CSA as an interconnected framework for resilient agricultural systems. Together, these findings illustrate CSA as an interconnected framework where knowledge supports the integration of climate adaptation, sustainability, livelihood enhancement, and policy engagement to foster resilient agricultural systems. The framework proposed according to the synthesis of CSA literature is largely aligned with the results of the similarity analysis, which are generally

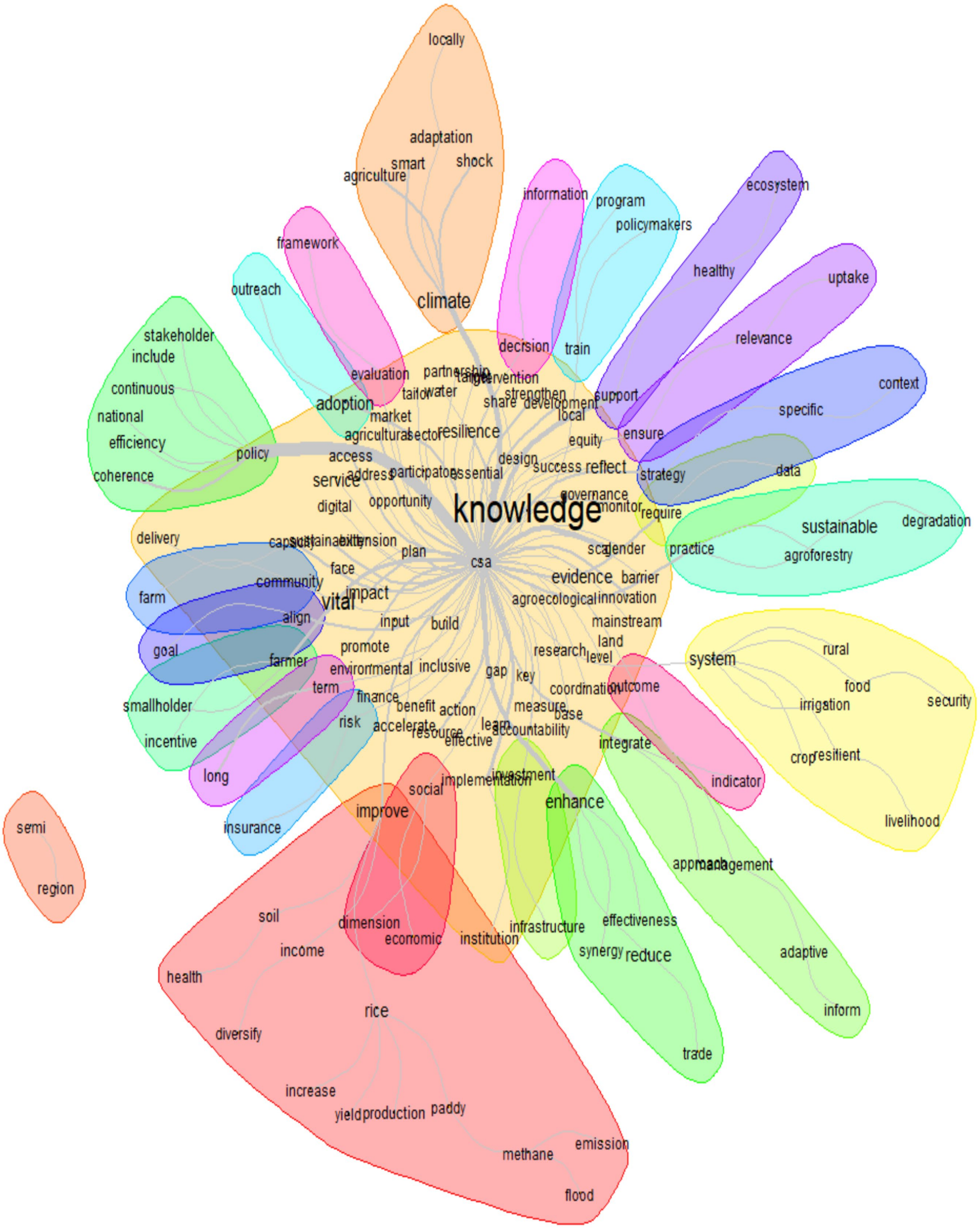

FIGURE 10
Results of similarity analysis.

consistent with the results gained with the help of the manual synthesis of literature.

4.2 Factorial correspondence analysis

Similarity analysis visually maps various segments linked to the core concept. To uncover relational clusters within the corpus of 61 articles, researchers suggest using factorial correspondence analysis. The outcomes of this approach are illustrated in Figure 11.

4.2.1 Hierarchical clustering and dendrogram

On the upper part of the image, the dendrogram is used to visually show the grouping of the most important terms or text parts of the dataset according to their closeness to each other. The dendrogram has each branch (or clade) of the tree representing how closely related the various clusters (classes) would be, where the height of the branch corresponds to the amount of difference between them. Branches that are lower imply more similarity whereas higher implicates more distinct thematic groups. This hierarchical arrangement will allow you to notice not only

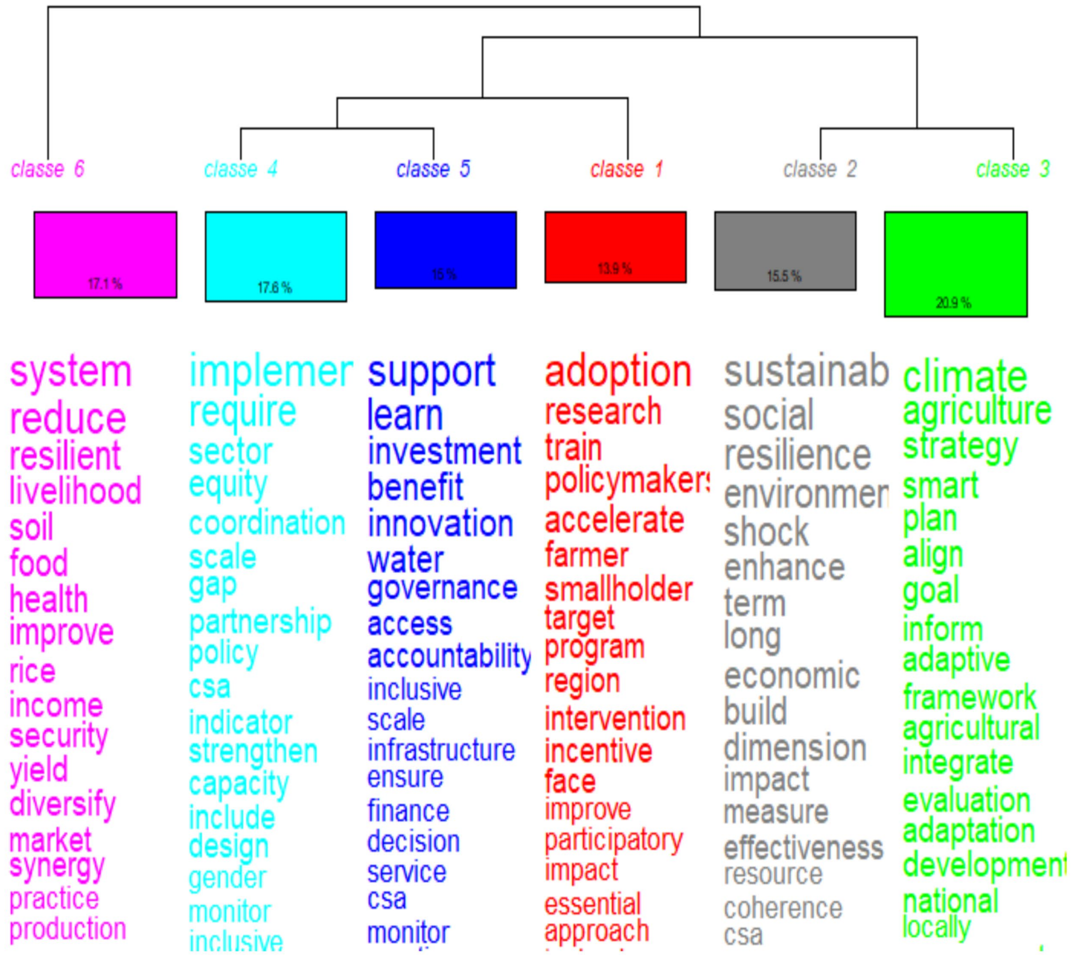

FIGURE 11
Dendrogramme with named clusters.

what terms group with one another, but also how the groups are connected to each other to show the multi-level, nested character of the discourse.

4.2.2 Classes and classical themes

The six classes (magenta, cyan, blue, red, gray, green) are symbolic of specific conceptual topic, and they are shown by the frequency with which certain words are used in the literature. The number in the bracket of each of the classes (e.g., 20.9% in the case of green) is the percentage of total variation in the data that the class accounts for in effect how popular or prevalent that theme is.

Class 1 (red, 13.9%): Themes of adoption and participation, which include terms such as research, train and farmer. This category represents the mechanisms and motivation towards adoption of new practices by the stakeholders.

Class 2 (gray, 15.5%): It focuses on sustainability and resilience with the following: social, economic and impact. The long-term effects and system capacity to resist shocks are the subject of this class.

Class 3 (green, 20.9%): Emphasizes climate and strategic planning, and such terms as climate, strategy, and adaptive. The centrality of integrative and forward-looking approaches in the literature is demonstrated by this class, which is the most prevalent.

Class 4 (cyan, 17.6%): Focuses on implementation and policy, and includes words like require, sector and coordination. It underscores the practical and institutional features of climate-smart agriculture such as the necessity to collaborate across sectors and have definite success indicators.

Class 5 (blue, 15%): Refers to support structures and governance and applies words such as investment, water and accountability. This is an indication that infrastructure, learning and responsible management are key towards enabling the sustainable practices.

Class 6 (magenta, 17.1%): Deals with resilience and livelihood at the system level, and such terms as resilient, livelihood, and synergy are present. This implies a holistic approach, in which the interdependence of agricultural systems is stressed, as well as the necessity of enhancing the overall security and well-being.

The most important thing is the percentage of variance developed under the influence of each of the classes: it estimates the extent to which each of the themes is contributing to the overall form of the discourse. The higher the percentage the more common or central is theme in the dataset. This assists in prioritizing on the areas that are the most influential in shaping the conversation in the field.

TABLE 1 PICO framework.

S. No.	Author	P (population)	I (intervention)	C (comparison)	O (outcome)
1.	Li T. et al. (2024)	83 rice farming sites across Thai Binh province, Red River Delta, Vietnam	Three rice management interventions: AWD + System of Rice Intensification principles (e.g., early transplanting, wider spacing, slow-release fertilizers, organic nutrients)	Baseline AWD rice management systems with regional variation in cultivar., density, fertilizer regimes and weed control that promotes root stimulation and plant growth.	Intervention2 (INV2: LTH31 cultivar with AWD irrigation) and Intervention 3 (INV3: BC15 cultivar., AWD irrigation) increased yields (INV2 > 50%), enhanced water-use efficiency, and reduced methane emissions under historical conditions; INV2 remained effective, with methane outcomes varying across different climate models.
2.	Tam and Shimada (2019)	352 rice farm households across Long An, Ben Tre, and Tra Vinh provinces, Vietnam to examine the factors affecting the performance of CSA and climate change adaptation response	Climate-smart agriculture participation (pilot programs) and self-driven climate change adaptation practices (e.g., changing sowing date, irrigation schedule, crop variety, input use)	Non-participation in CSA and/or no adaptation response	Adaptation increased technical efficiency by 13–14%; CSA adoption increased efficiency by 5–8%; agricultural extension, belief in climate change, land size, and proximity to water influenced participation
3.	Luu (2020)	350 rice farmers from 4 vulnerability zones (An Giang, Long An, Ben Tre, Tra Vinh); diverse socio-economic and agroecological contexts	CSA adoption via soil & water, yield, or weather risk management practices; assessed through multinomial logit modeling of farmer behavior	Non-adopters of CSA	Key drivers of CSA adoption: perception of climate change impact, education, farmland size, credit access, social capital, extension services, land tenure, and proximity to markets; significant variation across CSA types (soil/water vs. yield vs. weather risk)
4.	Pandeya et al. (2024)	200 rice farmers across four municipalities in Chitwan District, Nepal diverse agroecological zones and farm sizes	Adoption of CSA practices: pest- and drought-resistant varieties, efficient water management, diversified cropping, zero/minimum tillage, composting	Non-adoption of CSA practices	Education and climate group membership positively influenced adoption; farming experience, credit access, and larger farm size negatively associated; 72% overall adoption rate; policy suggestions include tailored credit, organizational strengthening, and CSA-specific training
5.	Onyeneke et al. (2021)	climate change perception and uptake of climate-smart agriculture in rice production in Ebonyi State, Nigeria using cross-sectional data from 347 rice farmers in an important rice-producing area in Nigeria.	Adoption of CSA practices (grouped via PCA into five bundles: crop/land management, climate-based services/irrigation, diversification/fertility, pesticides, nursery planting); drivers assessed through Multivariate Probit Model.	Non-adoption of CSA practices or response measures	CSA uptake influenced by perception of climate events (e.g., rainfall changes, temperature rise, floods); key determinants include education, age, household size, gender, farmer group membership, training; constraints include fertilizer cost, credit access, poor extension; PCA grouped CSA into 5 strategic packages for policy targeting
6.	Amarnath et al. (2023)	2,500 + smallholder maize and rice farmers across five districts (Ampara, Anuradhapura, Kurunegala, Monaragala, Vavuniya) during Maha and Yala seasons	Bundled services: weather index insurance (WII), climate advisories via SMS, climate-resilient maize and rice seeds, and agronomic support (fertilizer, water, pest management.)	Conventional farming with no bundled CSA support or insurance coverage	Bundled approach mitigated yield loss from moderate droughts, improved risk resilience, supported uptake of CSA practices; payouts reached up to 2,651/farmer, improved farmer confidence and engagement; business model enabled public–private scaling pathways

(Continued)

TABLE 1 (Continued)

S. No.	Author	P (population)	I (intervention)	C (comparison)	O (outcome)
7.	Tho et al. (2021)	506 rice smallholders from Vietnam Household Living Standards Survey (VHLSS) 2016, classified by farm size (≤2 ha and >2 ha)	Slack-Based Data Envelopment Analysis (SBM) to assess efficiency; promotion of eco-friendly farming packages, Large Field Model (LFM), and CSA practices like "One Must Do, Five Reductions."	Conventional fragmented farming with high chemical input use	Overall efficiency score (SBM) at 0.59; smaller farms (<2 ha) showed lower efficiency (0.54) and higher input slacks; reducing seed cost by 28 USD/ha, pesticides by 61 USD/ha, and fertilizers by 155 kg/ha recommended; Linear Farm Model (LFM) and CSA models improve efficiency and environmental outcomes
8.	Liang et al. (2024)	1,396 single-season rice farmers in Hubei Province; varied gender, education, credit access, soil texture, and farming experience	Adoption of Early-Maturing Crop Variety (EMCV) (average 110-day duration): shortened growing season, reduced exposure to climate shocks, lower chemical/fuel inputs, improved flexibility in farm operations	Non-adoption of EMCV (average 134-day duration); conventional rice varieties with higher climate exposure and input intensity	Early maturing Crop Varieties (EMCV) increased mean rice yield (+1.8%), reduced production risk and downside risk, and lowered GHG emissions per ha (−9.9%) and per ton (−30.6%); co-benefits across all three CSA pillars demonstrated via Klein–Vella Instrumental Variable (KV-IV) approach analysis
9.	Akinyi et al. (2022)	153 smallholder farmers across five SSA countries (Kenya, Nigeria, Ethiopia, Malawi, Zambia) in selected value chains: sweet potato, rice, faba beans, soybean, cassava, peanut, milk	Prioritized CSA practices identified using CSA Prioritization Framework (CSA-PF): improved seed varieties, good agricultural practices (GAP), and conservation agriculture (CA); evaluated through financial cost–benefit analysis (NPV, IRR, B/C ratio, PP)	Business-as-usual (BAU) farming without CSA interventions	All prioritized CSA practices showed positive NPV, IRR, and B/C ratios; highest NPV for GAP in Kenya's sweet potato (US$28,044, IRR 328%); lowest for CA in Malawi soybean (US$508, IRR 493%); lifecycle 5–20 years, payback period 1–2 years; practices sensitive to yield, price, and discount rates; externalities included biodiversity, air/water quality, labour intensity, and social co-benefits
10.	Tran et al. (2019)	579 rice-farming households across Thai Binh (North), Ha Tinh (Central), and Bac Lieu (South); 1,747 farming plots surveyed	Adoption of two CSATs: (1) water-saving technologies (WS), (2) improved stress-tolerant varieties (IS);	Plots with no CSA (WS_0IS_0); each CSA combination (WS_1IS_0, WS_0IS_1, WS_1IS_1) compared within and across provinces	CSA adoption increases net rice income (NRI), with the strongest gains from joint adoption (WS_1IS_1); impacts vary by province due to gender, age, land tenure, labor availability, climate stress exposure, soil fertility, access to markets, extension confidence, and risk attitude
11.	Zheng et al. (2024)	107 peer-reviewed studies (2013–2023) across Asia, Africa, Europe, and North America covering grain, cash, legume, and livestock systems	Diverse CSA practices grouped under five categories: land/soil management, seed use, chemical input use, water management, crop calendars/rotation; examined individually and as bundled interventions	Conventional farming systems lacking climate-adaptive innovations	CSA adoption improved: (i) crop yield & income (through enhanced efficiency, technical resource use); (ii) resilience via food consumption, dietary diversity & risk mitigation; (iii) environmental outcomes via lower GHGs and better soil health. Impacts varied by geography, crop type, CSA category, and metric—no one-size-fits-all strategy; bundles more effective than single practices
12.	Aravindakshan et al. (2021)	300 rice farmers across polder and non-polder zones in Barisal, Patuakhali, and Barguna districts; surveyed during rabi season using CE	Choice experiment comparing dry season crops: irrigated maize, wheat, boro rice, and mungbean vs. status quo (land fallowing); attribute levels included irrigation/fertilizer cost and net returns	Dry season land fallowing (status quo)	Farmers preferred mungbean (low-input, high-return) and maize over boro rice and wheat; strong negative preferences for high irrigation and fertilizer costs; willingness-to-invest positively associated with mungbean and maize returns

(Continued)

TABLE 1 (Continued)

S. No.	Author	P (population)	I (intervention)	C (comparison)	O (outcome)
13.	Vaiknoras et al. (2025)	900 rice-growing households across 75 villages in Lamjung, Tanahu, and Gorkha districts (Western Development Region), Nepal	Adoption of stress-tolerant rice varieties (STRVs); analysis via survey-design experiment, input measurement modules, and Correlated Random Effects modeling	Traditional varieties (TVs), old and new modern varieties (MVs), and hybrids	STRVs led to increased input use: +17 kg/ha early-season chemical fertilizer, +22 person-days/ha land prep labor, +21 kg/ha total fertilizer, +0.4 L/ha pesticide; yield ↑36%, yield variance ↓53% vs. TVs; crowd-in effects strongest for STRVs vs. other improved varieties; STRVs performed comparably to hybrids in yield variance and better than MVs for input mobilization even in non-drought years
14.	Mustafa et al. (2024)	400 wheat farming households across four climate-risk districts in Sindh Province; stratified by CSA adoption status	CSA practices (≥1 adopted for 3 + years): crop rotation with legumes, minimum tillage, stress-tolerant varieties, intercropping, furrow-bed planting; supported by CSA training and input provision	Non-adoption of CSA practices; conventional wheat farming under climate stress	CSA adoption increased wheat yield by 45.8% (ATT) and cost-efficiency by 7%; non-adopters could gain ~20% yield increase by adopting CSA; Endogenous Switching Regression (ESR) and Stochastic Frontier Analysis (SFA) models showed significant productivity and cost gains; key drivers included CSA training, education, cooperative membership
15.	Alemayehu et al. (2022)	733 smallholder farm households across inland valleys in Bouaké, Gagnoa (Côte d'Ivoire), and Ahafo Ano North & South (Ghana); stratified by 4 farm types based on land tenure and use	Use of Rural Household Multiple Indicator Survey (RHoMIS) for characterizing farming systems, food security status, poverty levels, and farmer perceptions of ecosystem services; extended survey covering agricultural, economic, and institutional indicators	Conventional analysis lacking ES integration and contextualized farm typologies for policy or CSA targeting	Large between-region variability in farm size, crop choice, and ES awareness; CSA adoption low, rice dominant across farm types, with 16–38% of households food-insecure and ~50% below poverty line; farmers rated provisioning ES (esp. food/water) and regulating ES (water storage, climate, pollination) highly; cultural ES awareness low; findings stress need for ES-informed CSA strategies tailored by farm type and region
16.	Jena et al. (2023)	494 smallholder paddy farmers in inland (Bolangir, Mayurbhanj) and coastal (Kendrapara) districts of Odisha, India	Adoption of two CSA practices: (1) Crop Rotation, and (2) Integrated Soil Management (gypsum, bunding, mulching); evaluated via multivariate probit and PSM	Non-adoption of CSA practices	Crop rotation raised income by 42–46% and yield by 1.5–2.5 q/acre; integrated soil management increased income by 27–34% and yield by 2.6–3.0 q/acre; key adoption drivers included access to extension, credit, seed subsidies, and farm electricity; complementarities between CSA practices statistically confirmed
17.	Luu (2020)	350 rice farmers across An Giang, Long An, Ben Tre, and Tra Vinh provinces, stratified by climate vulnerability and water zones	CSA practices grouped by category: (i) weather-risk management (e.g., insurance), (ii) soil and water management (e.g., "One Must, Six Reductions," Large Field Model), (iii) yield management (e.g., IPM, SRI, crop diversification); modeled via multinomial logistic regression	Non-adoption of CSA practices or traditional rice farming without CSA components	CSA adoption positively influenced by: education level, farm size, credit access, extension contact, perceived climate risks, land tenure security, and social capital; market constraints negatively affected adoption esp. for yield-focused CSAs; notable variation in adoption patterns by CSA type; findings support tailoring outreach by CSA pillar and vulnerability context

(Continued)

TABLE 1 (Continued)

S. No.	Author	P (population)	I (intervention)	C (comparison)	O (outcome)
18.	Lopez-Ridaura et al. (2018)	269 smallholder households in Bihar (Eastern Indo-Gangetic Plains); 5 typologies: part-time farmers, wealthy farmers, small-scale mixed farmers, medium-scale cereal farmers	Scenarios tested: (1) CSA practices (conservation agriculture); (2) improved livestock productivity; (3) drought stress	Baseline food security levels by typology without CSA; vulnerability and resilience across livelihood groups	Changes in household food security (e.g., potential food availability ratio), resilience to drought
19.	Mishra et al. (2024)	120 paddy farmers (60 each from climate-smart villages and non-climate-smart villages in Karnal & Kaithal districts, Haryana)	Structured interviews assessing CSA adoption barriers across three categories: economic, socio-personal, and technical constraints	Climate-smart village vs. non-households; impact of extension support and CSA awareness	CSV farmers face stronger economic barriers (e.g., high production cost, initial investments); non-CSV farmers face more severe technical constraints (lack of CSA awareness, training, and extension services); socio-personal barriers similar across groups; technical constraint gap statistically significant ($p < 0.01$)
20.	Abbasi and Nawaz (2020)	595 respondents from Punjab and Khyber Pakhtunkhwa, Pakistan; diverse education levels; smallholder and community farmers	Climate change awareness as assessed via structured questionnaire (7 items); predictive regression analysis of awareness on adaptations and constraints	Low-awareness farmers facing traditional climate risks without targeted adaptation support	Higher awareness significantly increases likelihood of adopting CSA practices ($R^2 = 0.446$, $\beta = 0.875$, $p < 0.001$); awareness also negatively correlated with perceived barriers to adaptation ($R^2 = 0.318$, $\beta = -0.707$, $p < 0.001$); awareness empowers proactive and context-specific adaptation decisions, but without systemic support, may increase anxiety or perceived helplessness
21.	Ha and Van Bac (2021)	214 rice farming households (Thai Nguyen Province); 118 CSA adopters vs. 96 non-adopters; selected from Dinh Hoa and Vo Nhai districts via random sampling	CSA practices (adoption of high-yielding varieties, System of Rice Intensification (SRI), drought-tolerant varieties, crop management, adjusted planting dates); analyzed via Propensity Score Matching (PSM) to control selection bias	Non-adopters applying conventional rice farming practices; potential overestimation of CSA benefits in uncontrolled studies	CSA adoption significantly improved rice yield (14–21%), total production value (≈26.7% gain), and reduced seed input (22–31.5%); no statistically significant changes in pesticide cost, labor days, or chemical fertilizer use; farmyard manure use slightly increased; education level, rice income proportion, and access to extension services were key drivers of CSA uptake
22.	Harahap et al. (2022)	44 lowland rice farmers in Teluk Mengkudu District (Serdang Bedagai Regency, Indonesia); exposed to CSA-focused training and extension activities	Multiple Linear Regression analysis of 5 factors affecting CSA interest: education, farming experience, innovation characteristics, role of extension agents, role of government	Varying levels of farmer interest and demographic/technical conditions; comparative influence of each variable on CSA uptake	High overall interest in CSA implementation (76.3%); strongest positive predictors: innovation characteristics (40.6%), farming experience (33.5%), extension role (35.5%); education (−14.7%) and local government role (2.7%) had negligible or negative influence; CSA adoption linked to increased productivity, structured farming (Emmanuel et al., 2024)

(Continued)

TABLE 1 (Continued)

S. No.	Author	P (population)	I (intervention)	C (comparison)	O (outcome)
23.	Emmanuel et al. (2024)	402 rice farmers sampled across 5 LGAs in Ebonyi State, Nigeria; predominantly smallholder, male (51.7%), secondary-educated (47.8%), experienced (>20 years)	Assessed effects of (1) climate change variables (temp, rainfall, windstorm, humidity, etc.) via multiple regression; (2) extension service access via Local Average Treatment Effect (LATE) & probit model	Farmers with poor or no access to extension services; increasing climate extremes (temp, rainfall, evaporation, storms)	Yield losses linked to extreme weather (temp, rainfall, evaporation, windstorms); relative humidity & atmospheric pressure positively affect yield; lack of extension access reduces yield by 84–96%; access improves yield by ~66%; top constraints: input costs, capital, labor, weak extension, herdsmen conflicts
24.	Nhat Lam Duyen et al. (2021)	579 rice-farming households across Bac Lieu (South), Ha Tinh (Central), and Thai Binh (North); stratified by gender and age; varying male out-migration levels	Surveyed perceptions of climate change, CSA technology adoption, workloads, decision-making authority (WEI), and youth engagement challenges	Regional differences in gender roles, labour contributions, empowerment, CSA adoption, and migration impacts	Women play larger roles in rice production in North/Central due to male out-migration; gender-neutral climate change perceptions but women cite more CSA adoption barriers; youth constrained by lack of access to land, credit, low profit, drudgery; targeted training, policy reform, youth incentives are recommended

4.2.3 Overall significance

The Factorial correspondence analysis (FCA) image offers a map of the intellectual topography of climate-smart agriculture by visually unravelling these complicated relationships. It demonstrates not only the main topics, but also the way they are connected to each other, and which of them is most important. This comes in particularly handy in systematic reviews, where they can be used to detect gaps in research, narrative dominance, and possibility of future research. The findings from the FCA can serve as an effective instrument of making sense in large and complicated textual data. It helps to see the underlying framework of the literature, understand in what way the major concepts are clustered, and quantify the significance of a specific theme- allowing a more strategic and informed research and analysis.

The lexicometric procedures employed in this review were directly selected to address Research Question 4 (RQ4). Specifically, the similarity analysis (Section 4.1) operationalises this question by mapping co-occurrence patterns between key terms across the 61-article corpus, revealing the conceptual proximity between sustainability, resilience, knowledge mobilisation, and methane mitigation as dominant discourse nodes. The factorial correspondence analysis and dendrogram (Section 4.2) extend this by quantifying the relative eight of each thematic class and showing how classes are hierarchically related thereby tracing he structural evolution of CSA discourse. The six classes generated (adoption/participation, sustainability/resilience, climate/strategic planning, implementation/policy, support/governance, and resilience/livelihood) map directly onto the intervention categories examined through PICO in Section 5, providing a cross-validation of the empirical synthesis. For instance, Class 3 (climate and strategic planning, 20.9%) and Class 6 (resilience and livelihood, 17.1%) together confirm that adaptation framing dominates the CSA-rice literature, a finding that substantiates the PICO outcome data showing widespread evidence for AWD, EMCV, and SRI as the most cited interventions. Class 1 (adoption and participation, 13.9%) corresponds directly to RQ1's focus on socioeconomic determinants of adoption, confirming that farmer training, extension contact, and participatory mechanisms are not only empirically important but lexically dominant in the literature. The lexicometric results thus do not stand alone as a separate descriptive output they function as an independent analytical lens that validates and deepens the PICO-based evidence synthesis.

5 PICO framework

The PICO framework is a method for developing focused clinical or research questions by identifying four elements Population, Intervention, Comparison, and Outcome as shown in Table 1. Researchers use these components to structure clear queries that guide evidence searches and data synthesis, making research both systematic and precise.

5.1 Population

> *RQ1:* What demographic and socioeconomic characteristics of rice-farming populations including farm size, gender, land tenure, and education level most significantly determine the adoption of climate-smart agriculture practices for methane mitigation and yield enhancement?

The demographic in each of this research is very different. Rice management interventions modeled on principles from the System of Rice Intensification were applied across 83 farming sites in Thai Binh province, Red River Delta, Vietnam to assess their potential for achieving both climate adaptation and mitigation goals, as demonstrated by Li T. et al. (2024). Tam and Shimada (2019) was conducted in Vietnamese provinces of Long AnTra Vinh and Ben Tre to examine the variables that have an effect CSA performance and climate change adaptation response on 352 rice farm households. To explore the application of climate smart agriculture in paddy production

(Onyeneke et al., 2021), examined the perspectives of people and use of climate change by using cross-sectional data of 347 rice farmers in Ebonyi State, a major rice-producing area in Nigeria. A sample of 300 rice farmers in polder and non-polder areas in the districts of Barisal, Patuakhali and Barguna was used in a study conducted by Aravindakshan et al. (2021) to examine heterogeneity in farmers preference of several dry season intensification options among alternative land fallowing dry season rice harvest against the status quo (dry season fallowing land after the monsoon season rice crop).

A multi-stage sampling method was employed to randomly choose 400 farm households from a climate-vulnerable province in Pakistan (Ha and Van Bac, 2021; Mustafa et al., 2024). Additionally, smallholder households were profiled across different regions and farm types using data from 400 randomly selected respondents situated in four agro-ecological zones: Bouaké and Gagnoa in Côte d'Ivoire, and Ahafo Ano North and South in Ghana (Alemayehu et al., 2022), In Ghana, Ahafo Ano South (Mishra et al., 2024) conducted a comparative study of the key challenges facing rice farmers in the eastern climatic zone of Haryana during the implementation of climate-sensitive farm practices. Adoption of CSA had impacted on key economic indicators among rice farmers was studied (Ha and Van Bac, 2021) 214 rice growing households in Thai Nguyen Province, 118 CSA adopters and 96 non-adopters, and were selected randomly, across the districts of Dinh Hoa and Vo Nhai. This study examined the impact of extension services and climate change on the productivity of rice farmers in Ebonyi State, Nigeria.

Addressing RQ1, the evidence across the reviewed studies consistently identifies extension service access, credit availability, education level, farm size, and perceived climate risk as the most significant socioeconomic determinants of CSA adoption in rice-farming populations. Extension contacts directly increased adoption probability in Vietnam (Ha and Van Bac, 2021), India (Jena et al., 2023), and Nigeria (Emmanuel et al., 2024). Credit access enabled smallholder farmers to invest in improved varieties and water management technologies (Luu, 2020; Pandeya et al., 2024), while land tenure security positively influenced adoption of soil and water conservation practices. Gender emerged as a critical but underexplored factor: women rice farmers in North and Central Vietnam reported greater adoption barriers despite contributing significantly to farm labour (Nhat Lam Duyen et al., 2021). Farmers with higher climate change awareness showed significantly greater likelihood of adopting CSA practice (Abbasi and Nawaz, 2020), though awareness alone without systemic institutional support increased perceived helplessness rather than adaptive action. These findings collectively indicate that socioeconomic enablers not agronomic knowledge alone are the primary determinants of CSA adoption in rice systems across diverse agroecological contexts.

5.2 Intervention

> *RQ2:* How do specific CSA interventions compare in their effectiveness for simultaneously reducing methane emissions and improving rice yield under varying agroecological and climatic conditions?

Rice grown using climate-smart methods manages the emission of methane and greenhouse gases, increases the productivity, and promotes food security. These interventions promote sustainable rice production by balancing environmental protection with agricultural resilience and yield improvement. Alternate wetting and Drying (AWD), a System of Rice Intensification approach that includes early transplanting, wider spacing, and organic nutrient use, represents an adaptive rice production intervention with potential climate mitigation co-benefits. However, its impacts remain uncertain under evolving climate trajectories (Li T. et al., 2024). The objective of climate-smart agriculture initiatives (pilot programs) is to enhance resistance to climate change, reduce greenhouse gas emissions, and optimize resource usage for sustainability. Rice farmers were exposed to agricultural services provided by the local government and institutions (Tam and Shimada, 2019). Climate-smart farming practices, including composting, diversification, no or limited tillage, resistant to pests and drought cultivars, and efficient water control are supposed to raise productivity and climate resistance (Pandeya et al., 2024).

Principal Component Analysis (PCA) was used to divide the adoption of CSA practices into five bundles, including food security, climate resilience and mitigation, pesticides, crop management, climate-based services, diversification, nursery planting to increase rice yield and revenue (Onyeneke et al., 2021). The agricultural season has been abridged, exposure to climate shock has been reduced, the levels of chemical use have been reduced, and flexibility in the operation of the farm has been achieved through the adoption of early flowering varieties of crops (average 110 days) (Liang et al., 2024). With the CSA Priorities Framework (CSA-PF) the following methods of conservation agriculture, good agricultural practices (GAP), and improved seed varieties were identified as priorities that could have a important impact on household food security, household income, and agricultural production (Akinyi et al., 2022). CSA methods like land/soil management, seed use, use of chemicals inputs, water management, and use of crop calendars/adoption of rotation techniques enhance the

TABLE 2 CSA effects across methane and GHG reduction.

CSA intervention	GHG reduction	Agroecological context	Source
Alternate Wetting and Drying (AWD)	20–50% methane reduction vs. continuous flooding	Lowland irrigated rice, Vietnam (Red River Delta, Mekong Delta)	Li T. et al. (2024) and Tho et al. (2021)
Early Maturing Crop Varieties (EMCV)	−30.6% GHG per tonne; −9.9% per hectare	Temperate single-season rice, Hubei Province, China	Liang et al. (2024)
SRI-based interventions (AWD + wider spacing + organic inputs)	Methane stabilized or reduced while yield increased >50%	Humid subtropical, Red River Delta, Vietnam	Li T. et al. (2024)
Bundled CSA (conservation agriculture + improved seeds + GAP)	Positive GHG reduction cited as co-benefit; not quantified at plot level	Sub-Saharan Africa (Nigeria, Ghana, Zambia, Kenya)	Akinyi et al. (2022)

TABLE 3 CSA effects across yield improvement.

CSA intervention	Yield effect	Farming system/ agroecological zone	Source
AWD + SRI (combined)	>50% yield increase (historical climate)	Lowland irrigated rice, Vietnam	Li T. et al. (2024)
Stress-Tolerant Rice Varieties (STRVs)	+36% yield; −53% yield variance vs. traditional varieties	Mid-hills rainfed/irrigated, Nepal	Vaiknoras et al. (2025)
SRI adoption (CSA package)	+14–21% yield; +26.7% total production value	Upland/hilly terrain, Thai Nguyen Province, Vietnam	Ha and Van Bac (2021)
Crop rotation (CSA practice)	+1.5–2.5 q/acre yield; +42–46% income	Coastal and inland rainfed rice, Odisha, India	Jena et al. (2023)
Integrated soil management (gypsum, bunding, mulching)	+2.6–3.0 q/acre yield; +27–34% income	Rainfed inland and coastal systems, Odisha, India	Jena et al. (2023)
EMCV (shortened growing season)	+1.8% mean yield improvement	Temperate single-season rice, Hubei, China	Liang et al. (2024)
Bundled CSA (One Must Do, Five Reductions + Large Field Model)	Improved technical efficiency; reduced input slacks	Fragmented smallholder lowlands, Mekong Delta, Vietnam	Tho et al. (2021)
CSA adoption (Pakistan wheat proxy)	+45.8% yield; +7% cost efficiency vs. conventional	Climate-risk districts, Sindh Province	Mustafa et al. (2024)
Bundled CSA – Sub-Saharan Africa	Positive NPV; payback period 1–2 years; biodiversity co-benefits	Mixed SSA agroecological zones	Akinyi et al. (2022)

TABLE 4 CSA effects across adoption rates and socioeconomic drivers.

Study context	Adoption rate/level	Key determining factors	Source
Chitwan District, Nepal	72% overall CSA adoption	Education, group membership; credit access and farm size negatively associated	Pandeya et al. (2024)
Ebonyi State, Nigeria	Moderate; varied by CSA bundle type	Farmer group membership, gender, age, extension access	Onyeneke et al. (2021)
Lowland Vietnam (4 provinces)	Varied by CSA pillar; weather-risk management lowest	Market access constraints; land tenure; social capital	Luu (2020)
North/Central/South Vietnam	Regional variation; women face greater barriers	Gender, migration patterns, land tenure	Nhat Lam Duyen et al. (2021)
Punjab and KPK, Pakistan	Adoption strongly predicted by awareness	$R^2 = 0.446$; $\beta = 0.875$ for awareness-adoption link	Abbasi and Nawaz (2020)
Haryana, India (CSV vs. non-CSV)	Higher in climate-smart villages	Economic barriers stronger in CSV; technical/awareness barriers higher in non-CSV	Mishra et al. (2024)
Teluk Mengkudu, Indonesia	76.3% interest in CSA	Innovation characteristics (40.6%), extension role (35.5%) were strongest predictors; education had negligible/negative effect	Harahap et al. (2022)

farm productivity and income through increased the crop yields and productivity, increased income and efficiency in use of technical and resources (Zheng et al., 2024). Stress tolerant rice varieties (STRV) can transform the agricultural sector and boost productivity of households (Vaiknoras et al., 2025). The Rural Household Multiple Indicator study (RHoMIS) is used to define farmer perceptions of ecosystem services, food security status, poverty levels, and farming systems; long-term study. These are the long term sustainable agricultural development plans which include the institutional, economic and agricultural variables (Alemayehu et al., 2022).

Addressing RQ2, the comparative evidence across interventions reveals that combined AWD and SRI practices produced the strongest dual outcomes, increasing yield by over 50% while reducing methane emissions under historical climate conditions in Vietnam's Red River Delta (Li T. et al., 2024; Li Y. et al., 2024). Early Maturing Crop Varieties reduced GHG emissions by 30.6%

TABLE 5 Comparative synthesis between Asia and Africa.

Dimension	Asia	Africa
Primary countries studied	Vietnam (Red River Delta, Mekong Delta, Thai Binh, Long An, Tra Vinh, Thai Nguyen), India (Odisha, Haryana), Bangladesh, Pakistan, Nepal, Sri Lanka, Philippines	Nigeria (Ebonyi State), Ghana (Ahafo Ano), Côte d'Ivoire (Bouaké, Gagnoa), Sub-Saharan Africa broadly
Dominant CSA interventions	Alternate Wetting and Drying (AWD), System of Rice Intensification (SRI), Early Maturing Crop Varieties (EMCV), Stress-Tolerant Rice Varieties (STRVs), bundled '1M5R + Large Field Model' (Vietnam), weather-index insurance + digital advisories (Sri Lanka)	Improved seed varieties, Conservation agriculture, Good Agricultural Practices (GAP), diversification strategies, Climate-Smart Village pilots, bundled CSA packages with short payback periods
Methane / GHG reduction evidence	Strong and quantified: AWD reduced methane by 20–50% vs. continuous flooding; EMCV cut GHG by 30.6% per tonne and 9.9% per hectare; SRI interventions decreased or stabilized methane while raising yields over 50%	Limited and largely unquantified at plot level; emphasis placed on overall GHG reduction as a co-benefit of bundled packages rather than methane-specific measurement
Yield improvement outcomes	Well-documented with high magnitudes: SRI in Vietnam +50% under historical climate; STRVs in Nepal +36% yield, −53% variance; CSA adoption in Thai Nguyen +14–21% yield, +26.7% production value; Crop rotation in Odisha +1.5–2.5 q/acre	Documented but less precisely quantified; Sub-Saharan Africa bundles showed positive economic returns with payback periods of 1–2 years; Pakistan wheat (proxy context) +45.8% yield, +7% cost efficiency upon CSA adoption
Socioeconomic drivers of adoption	Extension service access (Vietnam, India), credit availability, education level (strong positive effect in Vietnam: $\beta = 0.875$), farm size, perceived climate risk, gender barriers (women farmers in North/Central Vietnam face greater adoption constraints)	Extension contact, perceived climate risk, group membership; education effect is mixed or weak in Nigerian context; land tenure less formally studied; economic barriers (input costs) are the primary constraint
Policy & governance context	Strong national program alignment (Vietnam's climate-smart village initiative, India's conservation agriculture policy); extension systems relatively more institutionalized	Reliance on international donor frameworks and NGO-led programs; institutional extension systems less consistently available; policy coherence identified as critical gap
Key evidence gap	Simultaneous multi-season measurement of methane + N_2O + yield to resolve net global warming potential; long-term sustainability of bundled interventions under future climate scenarios (RCP 4.5/8.5)	Plot-level GHG quantification; gender-disaggregated adoption data; scalability evidence beyond pilot or donor-funded programs

per tonne and improved mean yield by 1.8%, offering a geographically transferable mitigation option applicable across diverse agro-ecological zones (Liang et al., 2024). Stress-Tolerant Rice Varieties increased yield by 36% and reduced yield variance by 53%, demonstrating strong climate resilience outcomes even under non-drought conditions (Vaiknoras et al., 2025). CSA adoption under SRI in Thai Nguyen Province, Vietnam, improved rice yield by 14–21% and total production value by approximately 26.7% compared to conventional farming (Ha and Van Bac, 2021). Crop rotation raised income by 42–46% and yield by 1.5–2.5 q/acre in Odisha, India, while integrated soil management increased income by 27–34% and yield by 2.6–3.0 q/acre (Jena et al., 2023). Across varying agroecological contexts, no single CSA intervention consistently achieved simultaneous methane reduction and yield improvement; rather, effectiveness was strongly mediated by hydrological conditions, soil type, and climate zone, confirming that context-specific intervention design is essential for achieving the triple-win outcomes of CSA.

5.3 Comparison

> *RQ3:* To what extent do bundled CSA interventions outperform conventional rice farming systems in terms of resource-use efficiency, climate resilience, and greenhouse gas reduction, particularly in climate-vulnerable smallholder contexts?

The analysis of traditional farming and climate-smart farming whereby, in the former, farmers are always flooded continuously, use massive amounts of chemicals, and generate high amounts of methane which does not augur well with the environment and climatic conditions. Conversely, climate-smart agriculture adopts water-efficient agriculture, combined nutrient management, and climate-resilient practices with an aim of improving sustainability, resource use, and climate resiliency in agricultural systems.

Conventional farming systems often relied on conventional tillage, monocropping, and high chemical input use, whereas CSA practices promote conservation agriculture, crop diversification, and resource-efficient inputs leading to improved yields, resilience, and reduced greenhouse gas emissions (Zheng et al., 2024). Plots planted with STRVs will receive more early-season inputs from farmers than traditional varieties (TVs) of rice. This is attributable to the progression of the season, which diminishes the probability of climate shock, the adverse risk effect, the amalgamation of revenue, the implications of downside risk, and marginal productivity (Vaiknoras et al., 2025). Traditional farming in Sri Lanka relied on rainfed systems, non-resilient seed varieties, and limited climate information, whereas the CSA bundle introduced drought-tolerant seeds, satellite-based weather index insurance, and the real-time agronomical advisories resulting in improved resilience, financial protection, and adaptive decision-making for smallholder farmers (Amarnath et al., 2023).

Addressing RQ3, bundled CSA interventions consistently and substantially outperformed both conventional rice farming systems and single-practice CSA approaches across all performance dimensions. Zheng et al. (2024), synthesising 107 peer-reviewed studies, confirmed that bundled CSA practices delivered simultaneous improvements in crop yield, income, climate resilience, and GHG reduction, with no single-practice strategy achieving equivalent outcomes. In the Vietnamese Mekong Delta, the One Must Do Five Reductions and Large Field Model bundle significantly improved technical efficiency and reduced input slacks in fertilizer, pesticide, seed, and labour compared to conventional smallholder farming (Tho et al., 2021). In Sri Lanka, bundling climate-resilient seeds with weather index insurance and real-time digital advisories reduced crop losses and enabled timely adaptive decisions during climate shocks outcomes that neither component achieved independently (Amarnath et al., 2023). In Sub-Saharan Africa, bundled CSA interventions delivered strong economic returns with payback periods of one to two years and significant biodiversity and water quality co-benefits (Akinyi et al., 2022). CSA adoption in Pakistan increased wheat yield by 45.8% and cost efficiency by 7% compared to conventional farming, with non-adopters projected to gain approximately 20% yield increase upon adoption (Mustafa et al., 2024). These findings confirm that bundling is not merely additive but produces synergistic outcomes that exceed the sum of individual practice effects, particularly in climate-vulnerable smallholder contexts where single interventions are insufficient to absorb the complexity of compounding climate and market risks.

Traditional rice farming in the Mekong Delta was marked by fragmented landholdings and excessive input use, leading to inefficiencies and environmental degradation. Adoption of climate-smart agriculture (CSA) techniques like "One Must Do, Five Reductions" encourages using certified seeds while reducing seed rates, fertilizers, pesticides, water use, and post-harvest losses to improve efficiency and sustainability in rice farming and achieve higher productivity and better market access significantly improved technical efficiency, reduced input slacks, and promoted sustainable intensification (Tho et al., 2021). Traditional rice farming in Hubei relied on longer-duration varieties with higher exposure to climate shocks and greater input intensity, whereas CSA practices using early maturing crop varieties shortened the growth cycle, reduced yield variability and greenhouse gas emissions, and enhanced climate resilience and productivity (Liang et al., 2024). Traditional farming across sub-Saharan Africa relied heavily on rainfed systems and low-resilience practices, whereas CSA interventions such as improved seed varieties, conservation agriculture, and better agricultural practices enhanced productivity, reduced climate vulnerability, and delivered strong economic returns with short payback periods (Akinyi et al., 2022). Traditional dry-season farming in coastal Bangladesh often involved land fallowing due to high irrigation costs and climate risks, whereas CSA practices such as low-input mungbean and surface-water irrigated maize offered farmers more resilient, profitable alternatives aligned with their preferences for reduced investment and improved net returns (Aravindakshan et al., 2021).

5.4 Outcome

Practices of the Climate-Smart Agriculture provide significant benefits to the farm systems, such as greater effectiveness, more stable farmer earnings, less crop risk, policy congruence, flexibility and greater support of biodiversity. The findings highlight the significance of combining CSA strategies to ensure sustainable development as well as climate-resistance in agriculture is realized.

In the conditions of historical climate, two SRI interventions decreased methane emissions but also increased yields dramatically (by over 50 percent). These measures also increase yield in future climatic conditions as compared to a baseline climate change even reduces the absolute yields of the management strategies (Li T. et al., 2024). The Early Maturing Crop Varieties (EMCV) reduced GHG emissions per ton (−30.6%), per ha (−9.9%), reduced production risk and downside risk, and improved the mean rice yield (+1.8%) (Liang et al., 2024). CSA adoption led to improved agricultural productivity and incomes, as through efficiency, usage of technical resources, resilience in form of food intake, nutritional diversity and risk mitigation, environmental impact in terms of reduced GHGs, and better soil health (Zheng et al., 2024). Stress-tolerant rice varieties (STRVs) are high-yielding modern rice varieties (MVs) that have been engineered to cause minimal losses in yield when subjected to weather stressors (Vaiknoras et al., 2025).

The CSA bundle enhanced smallholder resilience by integrating climate-resilient seeds, weather index insurance, and real-time advisories. It led to reduced crop losses, timely decision-making, and financial protection during climate shocks (Amarnath et al., 2023). Adoption of climate-smart practices specifically the "One Must Do, Five Reductions" (1M5R) and Large Field Model (LFM) led to significantly improved technical efficiency, reduced input slacks (fertilizer, pesticide, seed, labor), and enhanced sustainability for rice smallholders across varying farm sizes (Tho et al., 2021).

5.5 Critical synthesis

Across the 61 studies reviewed, the evidence on CSA effectiveness in rice systems converges on three consistent findings, but with important qualifications that the existing literature has not adequately addressed.

5.5.1 On methane reduction

AWD is the most widely studied mitigation practice, and studies from Vietnam's Red River Delta and Mekong Delta consistently report methane reductions of 20–50% under AWD compared to continuous flooding (Li Y. et al., 2024; Tho et al., 2021). However, this range reflects significant variation driven by soil type, temperature, and groundwater depth rather than the practice itself. Early Maturing Crop Varieties (EMCV) achieve methane reductions of up to 30.6% per tonne of rice produced (Liang et al., 2024), suggesting that varietal selection may offer more geographically generalizable mitigation outcomes than water management alone. Critically, no study in this corpus simultaneously measures methane flux, nitrous oxide (N_2O) emissions, and yield over multiple seasons, meaning the net global warming potential of most CSA practices remains unresolved. This is a significant evidentiary gap that prevents confident policy recommendations.

5.5.2 On yield improvement

CSA adoption improved yield across all study contexts, but the magnitude varied substantially. SRI-based interventions in Vietnam produced yield increases exceeding 50% (Li T. et al., 2024; Li Y. et al., 2024), while STRVs in Nepal raised yield by 36% and reduced yield variance by 53% (Vaiknoras et al., 2025). Bundled interventions outperformed single practices: (Zheng et al., 2024) while synthesising 107 studies, found that bundled CSA consistently exceeded conventional farming on yield, resilience, and GHG metrics, with no single-practice strategy achieving equivalent outcomes. However, this bundling advantage comes with adoption barriers: Mishra et al. (2024) found that farmers in climate-smart villages faced higher economic barriers (input costs, initial investment) than non-adopters, while non-adopters faced greater technical and awareness constraints. This suggests that adoption costs and awareness deficits operate in opposite directions across farmer typologies a nuance that aggregate adoption rate figures in most studies obscure.

5.5.3 On socioeconomic drivers

The most consistently significant determinants of CSA adoption across South Asia and Southeast Asia were: extension access, education level, farm size, credit availability, and perceived climate risk. These were reported in eleven of the twenty-one adoption-focused studies in this corpus (Ha and Van Bac, 2021; Luu, 2020; Pandeya et al., 2024). However, the direction of some associations was inconsistent. Harahap et al. (2022) found education level to have a negligible or negative effect on CSA interest, while Abbasi and Nawaz (2020) found it strongly positive ($\beta = 0.875$). This inconsistency likely reflects the different educational thresholds across study contexts and the confounding role of extension quality: in contexts where extension services are strong, education has less marginal effect on adoption because information access is not the binding constraint.

5.5.4 Comparison with non-rice and global CSA evidence

The CSA effectiveness documented for rice in this review is broadly consistent with the findings of Zheng et al. (2024) across diverse crop systems, but the rice-specific context introduces two distinctive features not present in upland crop systems: the centrality of water management as both a yield determinant and a methane driver, and the greater vulnerability of smallholder rice farmers to weather index insurance gaps. The Sri Lanka case (Amarnath et al., 2023) demonstrated that bundling satellite-based insurance with climate-resilient seeds produced resilience outcomes that neither component achieved independently a finding not replicated in the non-rice literature reviewed herein, suggesting that insurance integration may be particularly consequential in flooded rice systems.

5.6 Quantitative aggregation of CSA effects across agroecological contexts

5.6.1 Methane and GHG reduction—aggregated magnitudes

Across the reviewed corpus, methane reduction estimates vary substantially by intervention type and agroecological setting:

The Table 2 reveals a clear north–south asymmetry in GHG measurement capacity. Asian contexts particularly Vietnam and China provide precise methane flux data measured across seasons and management scenarios, enabling rigorous comparison. In contrast, African contexts frame GHG reduction primarily as a co-benefit of bundled CSA without plot-level quantification. This asymmetry is not merely a reporting difference; it reflects underlying disparities in monitoring infrastructure, extension research capacity, and climate finance linkages. Policies targeting methane-linked carbon credits in rice systems (e.g., REDD+, Voluntary Carbon Markets) will therefore be more readily implemented in Asian than in African contexts, reinforcing existing inequalities in climate finance access.

Furthermore, the range of methane reductions attributed to AWD (20–50%) does not represent measurement error alone it encodes critical interactions with soil type (anaerobic soils produce more methane), groundwater depth (shallow water tables limit the drying effect), and temperature (higher temperatures accelerate methanogenesis even during drying). No study in this corpus simultaneously measures methane, nitrous oxide (N_2O), and yield across multiple seasons, meaning the net global warming potential (GWP100) of most CSA practices remains unresolved. Until this evidentiary gap is closed, policymakers should treat published methane reduction figures as context-specific estimates rather than generalizable benchmarks.

5.6.2 Yield improvement—aggregated effects across agroecological zones

Yield improvement estimates drawn from the reviewed studies range from modest to substantial depending on intervention type, agroecological zone, and baseline farming system:

From the Table 3, three patterns emerge from this aggregation. First, the magnitude of yield gains is highest in contexts where the baseline farming system is most inefficient or resource-constrained particularly where conventional flooding, unimproved varieties, and fragmented landholdings are the norm. This implies that reported effect sizes are partly baseline-dependent and may overstate benefits in contexts where conventional systems are already relatively efficient. Second, bundled interventions consistently outperform single-practice approaches but this bundling advantage comes with compounding adoption barriers including higher input costs and greater technical complexity. Third, the most dramatic yield improvements such as SRI's > 50% gains in Vietnam occur under historically favorable climatic baselines; under future RCP 4.5 and RCP 8.5 scenarios, these gains are projected to diminish as absolute yields decline, underscoring the importance of scenario-specific evaluation.

5.6.3 Adoption rates and socioeconomic drivers—comparative evaluation across agroecological contexts

A critical comparison of adoption levels across contexts reveals that adoption is not a uniform function of technology quality, but is strongly mediated by agroecological and institutional context:

These findings from the Table 4 expose a fundamental heterogeneity that aggregate adoption statistics obscure. Adoption constraints operate in opposite directions across farmer typologies: in climate-smart village contexts (Mishra et al., 2024), economically capable farmers face higher investment costs as the binding constraint, while non-adopters lack technical knowledge and extension access. This dual barrier structure means that a single policy instrument whether a subsidy, a training program, or an insurance scheme is unlikely to address both constraint types simultaneously. Notably, the effect of education on adoption is inconsistent across contexts. Abbasi and Nawaz (2020) found a strong positive effect ($\beta = 0.875$), while Harahap et al. (2022) found education to have a negligible or slightly negative influence. This inconsistency is not contradictory; it reflects the role of extension quality as a confounding variable. In contexts with strong, accessible extension systems, formal education has less marginal impact on CSA uptake because farmers can obtain decision-relevant knowledge through institutional channels. In information-poor environments, education becomes more decisive because it enables self-directed knowledge acquisition. Policy design should therefore account for the interaction between education and extension density.

Gender represents a consistently underexplored moderating variable. Women rice farmers in North and Central Vietnam reported greater adoption barriers than men despite contributing substantially to farm labor (Nhat Lam Duyen et al., 2021). Gender-disaggregated adoption data were absent or incomplete in the most reviewed African studies, representing a critical evidence gap for equity-sensitive policy design.

5.7 Regional comparative synthesis: Asia and Africa

The regional comparison (Table 5) reveals a clear asymmetry between Asia and Africa across all evaluated dimensions. Asian contexts, particularly Vietnam, India, and Nepal, demonstrate well-quantified CSA outcomes AWD reducing methane by 20–50%, SRI improving yields by over 50%, and STRVs cutting yield variance by 53% supported by institutionalized extension systems and strong national policy frameworks. These precise, causally grounded estimates are largely products of rigorous counterfactual methodologies and sustained government-backed research infrastructure. In contrast, African evidence remains largely qualitative at the GHG level, with emissions reduction framed as a co-benefit rather than a measured outcome. Yield and economic returns are positive but reported at aggregate levels, with payback periods of 1–2 years serving as the primary performance metric. Extension systems are less consistent, and CSA programmes rely heavily on donor-funded pilots, raising concerns about long-term scalability and institutional continuity.

Critically, both regions share common socioeconomic adoption drivers such as extension access, perceived climate risk, and group membership but the binding constraints differ. In Asia, gender barriers and credit access are the primary gaps; in Africa, high input costs and technical awareness deficits dominate. Gender-disaggregated adoption data are notably absent from most African studies, a significant gap given women's substantial role in smallholder rice production. Overall, the evidence base is geographically imbalanced. This imbalance is not inherent to the regions' agricultural potential but reflects unequal investment in monitoring infrastructure and institutional capacity a disparity that, if unaddressed, risks skewing global CSA investment and carbon finance toward already well-resourced Asian contexts.

6 Limitations

The methodology employed to locate pertinent articles may be deficient. There exists a possibility that pertinent research excluded from the Scopus and Web of Science databases was not recognized. The research designs, sample sizes, and methodologies of the included studies may vary. Various study designs, including qualitative, quantitative, and experimental methodologies, might affect the quality and trustworthiness of the synthesized data overall. It concentrates exclusively on CSA activities related to rice, rather than enhancing applicability. The analysis fails to assess the trade-offs between yield improvements and ecosystem services, which are crucial for a comprehensive evaluation of Climate-Smart Agriculture (CSA). Additionally, the restriction to English-language and open-access articles may have introduced publication bias and limited geographic representativeness. Relevant studies published in other languages or subscription-based journals may not have been captured, potentially excluding important regional insights into CSA practices.

7 Future findings

Findings and limitations from studies evaluating climate-smart agriculture (CSA) practices in rice cultivation indicate several focused directions for future research. More meta-analytical assessments across diverse agroecological contexts are required to generate robust estimates of methane mitigation and yield effects, disaggregated by farm typologies, climatic exposure, and resource access. Typology-based decision frameworks are critical for classifying CSA practices according to farm size, socioeconomic status, and climate risk exposure, thereby informing targeted policy design, extension strategies, and investment planning. Greater attention must also be given to gender and youth dynamics in CSA adoption, particularly in regions affected by male out-migration and generational disengagement, through interventions such as land access reforms, gender-sensitive incentives, and inclusive training.

Digital tools and decision-support systems, weather-index insurance, and SMS-based advisories, should be rigorously evaluated for scalability, user engagement, and contributions to resilience and productivity across varied socioeconomic settings.

Further research should examine synergies, trade-offs, and co-benefits of bundled CSA practices such as alternate wetting and drying (AWD), stress-tolerant rice varieties (STRVs), and composting, using multi-criteria analysis to assess impacts on productivity, resilience, and environmental outcomes. Aligning CSA results with SDGs 2, 12.3, and 13.2 through indicator-based monitoring frameworks can strengthen reporting and accountability. Additionally, choice experiments and behavioral modeling can guide incentive design under different subsidy, credit, and extension scenarios. Future research should also evaluate trade-offs between yield gains and ecosystem services, and strengthen monitoring, evaluation, and learning systems, including participatory tools to support adaptive management over time.

8 Conclusion

This systematic review provides a comprehensive synthesis of climate-smart agricultural practices (CSAPs) in rice cultivation, combining the PICO framework, bibliometric analysis, and lexicometric analysis to connect technical outcomes with broader thematic and policy insights. Through the PICO framework, the review shows that rice-farming populations across diverse agro-ecological zones are highly vulnerable to climate change, and adoption of CSAPs is shaped by socioeconomic factors such as farm size, gender, education, and land tenure. Interventions including alternate wetting and drying (AWD), biochar application, and the system of rice intensification (SRI) consistently reduced methane emissions while improving yield, water productivity, and soil health. Compared to conventional rice farming systems, CSAPs delivered superior resource-use efficiency, climate resilience, and greenhouse gas mitigation, particularly in smallholder contexts. The outcomes confirm a "triple-win" higher productivity, reduced methane emissions, and strengthened resilience. The bibliometric analysis revealed a rapidly expanding and geographically diverse research landscape, marked by strong interdisciplinary collaboration and increasing publication in sustainability-focused journals. This growth reflects the rising global importance of CSA in rice systems and provides evidence of knowledge diffusion across regions and disciplines. The lexicometric analysis highlighted discourse convergence around sustainability, resilience, and innovation, showing how CSA research has evolved conceptually over time. These thematic clusters demonstrate that CSA is increasingly framed not only as a technical solution but also as a holistic pathway to food security, climate resilience, and sustainable development.

Altogether, the integration of PICO, bibliometric, and lexicometric findings establishes that CSAPs are central to achieving global climate goals and directly support the UN Sustainable Development Goals (SDGs). By consolidating empirical evidence and mapping thematic trends, this review provides a robust foundation for future research, policy development, investment strategies, and outreach programs aimed at scaling CSA adoption in rice-growing regions. Future studies should prioritize bundled CSA interventions, deepen cross-regional synthesis, and integrate socioeconomic dimensions more fully to accelerate adoption in climate-vulnerable contexts.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

RD: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. PM: Methodology, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declared that Generative AI was not used in the creation of this manuscript.

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