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REVIEW ARTICLE

Climate-smart agriculture technologies: Trends, acceptance and adoption constraints among farmers - A systematic literature review and bibliometric analysis

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Abstract

Climate-smart agriculture (CSA) represents a transformative approach to addressing the multifaceted challenges posed by climate change to global agriculture. This review comprehensively analyses CSA adoption trends, acceptance factors and barriers, utilizing systematic literature review and bibliometric analysis methodologies. The findings underscore CSA's potential to enhance resilience, boost productivity and mitigate environmental impacts through practices such as agroforestry, precision agriculture and water-efficient irrigation. However, its widespread adoption is hindered by socio-economic, institutional and ecological constraints, including limited access to credit, inadequate extension services, high initial investment costs and socio-cultural challenges such as gender disparities. Key findings reveal that financial incentives, robust policy support and tailored extension services are critical drivers of CSA adoption. Digital tools, such as Digital Advisory Services (DAS), effectively bridge knowledge gaps by delivering timely, localized information to farmers. Gender-sensitive interventions and the strengthening of community networks are also emerge as vital components in overcoming adoption barriers, fostering inclusivity and collective action. Additionally, the analysis underscores the importance of region-specific strategies that integrate traditional agricultural knowledge with modern CSA practices to address local environmental and cultural contexts. This article provides actionable recommendations, including enhancing institutional support, scaling digital outreach and implementing consistent policy frameworks to promote CSA. By addressing these multidimensional barriers, CSA can make a significant contribution to sustainable agricultural systems, ensuring food security, improving resilience and reducing greenhouse gas emissions in the face of a changing climate.

Keywords: climate mitigation strategies; climate-smart agriculture (CSA), digital advisory services (DAS); resilience; sustainable agriculture

Introduction

Climate change poses significant challenges to global agriculture, threatening food security, livelihoods and ecosystem sustainability (1). Farmers increasingly face pressures from extreme weather events, fluctuating climate patterns and the degradation of natural resources. In response to CSA has emerged as a transformative approach, offering strategies to boost resilience, increase productivity and reduce greenhouse gas emissions (2). By aiming to improve the adaptive capacity of farming systems, CSA seeks to ensure food security while minimizing agriculture's environmental footprint (3). As the effects of climate change intensify, CSA is gaining prominence among policymakers, researchers and practitioners, as a viable pathway toward sustainable agricultural development.

Despite its considerable potential, the widespread adoption of is hindered by various barriers. Socioeconomic, cultural and institutional challenges frequently constrain farmers' ability to implement CSA practices. Research highlights key challenges, such as restricted access to credit, inadequate extension services and socio-cultural constraints, including gender disparities that limit women's participation in CSA initiatives (4). In support of this, data shows that women users (20.2%) and non-users (6.5%) in male-headed households have significantly lower access to extension services compared to men (83.7%) (5). Addressing these barriers is essential to make CSA accessible to all farmers, especially those most vulnerable to the impacts of climate change (6).

Knowledge dissemination and awareness play a crucial role in CSA adoption. Extension services and farmer cooperatives are instrumental in bridging knowledge gaps and offering technical support for CSA (7, 8). However, the effectiveness of these support mechanisms often varies, influenced by the availability of skilled personnel and the institutional capacity of service providers (8). Recently, digital advisory services have helped extend outreach efforts by delivering timely information on climate risks and adaptive practices to farmers (9). Nevertheless, many smallholder farmers, especially those in remote areas, remain disconnected from these vital information networks, thereby limiting their access to essential CSA knowledge.

Adoption rates of CSA practices vary widely based on region and farmer demographics. In sub-Saharan Africa, smallholders often face challenges such as limited access to inputs, market instability and inadequate infrastructure, all of which hinder the CSA adoption (10). In contrast, areas with better market access and infrastructure, like parts of Latin America, show more success with climate-resilient agricultural practices (11). These regional disparities underscore the need for region-specific strategies that address unique socio-economic and environmental conditions.

Furthermore, research increasingly underscored the critical role of social capital in facilitating CSA adoption. Elements like community networks, mutual trust and social cohesion significantly influence farmers' decisions to adopt CSA, enabling knowledge-sharing and collective action (12). Initiatives like farmer field schools and participatory training programs have proven effective in fostered these networks, encouraging collective CSA adoption (13).

Strengthening social structures can help overcome adoption barriers, especially in communities lacking formal extension services. Technological integration in CSA practices also holds great promise for enhancing agricultural resilience. Precision agriculture, weather forecasting tools and mobile-based advisory platforms empower farmers with data-driven insights, enabling them to optimize resource use and boost productivity (14). Among these, digital platforms, in particular, play a valuable role in informing farmers about climate risks and available adaptation strategies, thereby mitigating their vulnerability (15). However, the adoption of such technologies is often constrained by challenges related to digital literacy, affordability and connectivity, especially in rural regions (16). Bridging these digital divides is critical to ensure that technological advancements benefit all farmers equitably.

Environmental conditions, including soil quality, rainfall patterns and temperature fluctuations, also play a significant role in the CSA adoption. For instance, agroforestry practices that effectively mitigate soil erosion in one region may not be suitable elsewhere with different climate patterns (17). This highlights the need for context-specific research and locally adapted strategies to maximize the effectiveness and relevance of CSA interventions.

In this review article, the study intends to present in-depth analysis through systematic literature review (SLR) and bibliometric analysis, with the following objectives:

1. To examine trends in the adoption of climate-smart technologies.
2. To analyze factors influencing farmers' acceptance of CSA.
3. To identify challenges and barriers to adopting CSA in agriculture.
4. To provide recommendations to promote CSA adoption among farmers.

Climate change and its global impact on agriculture

Background on climate change and its impact on agriculture

Climate change has emerged as one of the most critical global challenges, significantly impacting agriculture worldwide. Rising temperatures, unpredictable rainfall patterns, an increasing frequency of extreme weather events and rising sea levels have contributed to reduced crop yields, the degradation of of arable land and increased vulnerability among farming communities. Reports from the Intergovernmental Panel on Climate Change (IPCC) indicates that climate-induced changes in agricultural conditions have resulted in declining productivity, especially in tropical and subtropical regions, leading to severe food security concerns (18).

Agricultural losses at a global level due to climate change

Agriculture worldwide has experienced substantial losses due to the impacts of climate change. According to estimates by the Food and Agriculture Organization (FAO), climate-related disasters have cost the global agricultural sector over $96 billion in crop and livestock losses over the past decade (19). Rising temperatures have resulted in heat stress in crops, reduced soil moisture levels and increased pest outbreaks, all of which have contributed to significant declines in agricultural productivity across various regions. Extreme droughts in Africa, frequent cyclones in South and Southeast Asia and widespread wildfires in Australia and the United States have further aggravated these problems (20).

Climate change-affected regions and strategies for mitigation

Climate change has severely impacted agriculture across multiple regions, necessitating the implementations of diverse mitigation strategies to safeguard food security and livelihoods. A global map (Fig.1) highlighting the regions most affected by climate change. In Thailand, recurrent droughts and floods have disrupted rice production, prompting the government to implement sustainable water management strategies and promote drought-resistant crop varieties (21). Similarly, Bangladesh, a low-lying country, faces rising sea levels and frequent cyclones, resulting in significant agricultural losses. To combat this, initiatives such as floating farms, salt-tolerant crops and embankment constructions have been introduced to protect farmlands (22).

In the Philippines, frequent typhoons and heavy rains cause soil erosion and crop damage, making disaster preparedness training for farmers and the enhancement of seed banks critical for adaptation (23). Likewise, India has experienced extreme heat waves and erratic monsoon patterns, leading to severe water stress in major agricultural regions. As a response, the government has promoted organic farming, micro-irrigation and the establishment of climate-smart villages through initiatives such as the National Adaptation Fund for Climate Change (NAFCC) and the promotion of climate-resilient crops like millets (24).

Indonesia, facing rising sea levels that threaten coastal rice-growing areas, has implemented adaptation strategies like

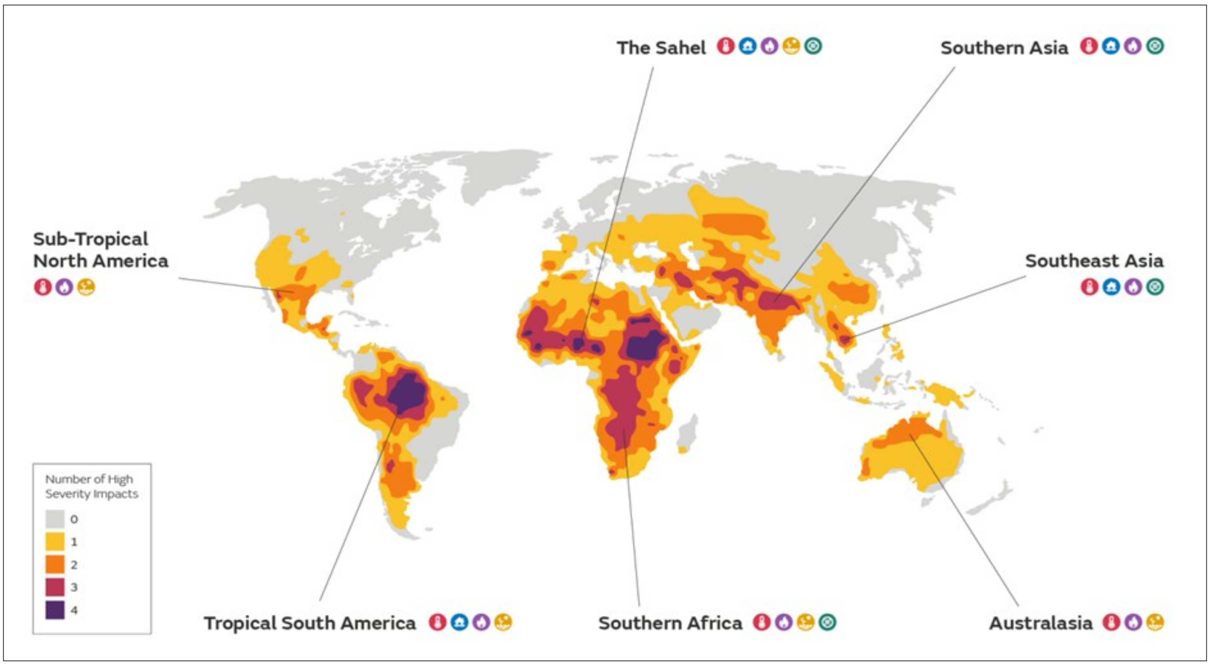

Fig. 1. The global map highlighting the regions most affected by climate change (78).

improved drainage systems and floating rice cultivation (25). Meanwhile, in coastal regions of Africa, countries such as Senegal and Nigeria are grappling with prolonged droughts and desertification, leading to food insecurity. Reforestation projects such as the Great Green Wall Initiative, along with solar -powered irrigation systems and community-led adaptation programs, have been introduced to mitigate these challenges (26). Across all these regions, the adoption of climate-smart agricultural practices, including agroforestry, sustainable irrigation techniques and resilient crop diversification, are crucial for sustaining food production and minimizing the adverse effects of climate change.

CSA offers a comprehensive approach to transforming and reorienting agricultural systems in a way that ensure food security while simultaneously addressing climate change (27). The CSA approach integrates:

Sustainable Land Management: Practices such as conservation agriculture, agroforestry and improved soil health practices.

Precision Agriculture: Integration of IoT, AI-driven weather forecasting and satellite imagery for efficient resource management.

Resilient Crop Varieties: Development of deployment of genetically modified and climate-resilient seeds to withstand extreme environmental conditions.

Water Management: Techniques including drip irrigation, rainwater harvesting and desalination techniques.

Community Engagement: Empowering farmers through education, participatory research and knowledge-sharing platforms.

Methodology

In scholarly research, a systematic literature review (SLR) is a comprehensive and methodical technique used to locate, find, assess and synthesize existing literature on a particular research issue or topic. The SLR approach enables researchers to systematically explore, analyze and interpret research issues or phenomena of interest (28). Both bibliometric analysis and a systematic literature review were used to identify emerging trends in CSA. The SLR method is especially effective in identifying research gaps within the existing body of literature and in contributing to the advancement of academic knowledge. For this review, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) criteria were followed, as illustrated in Fig. 2. The following steps were taken to conduct the review:

Document search

The study started with the identification of relevant documents, which were retrieved from the Scopus database. Research articles were identified using specific keyword combinations. The selection of keywords was initially based on examples from previous studies (29). The final search string was subsequently refined through necessary modifications and expert consultation.

Article screening

First, the articles were filtered based on preset inclusion and exclusion standards. Editorial letters, gray literature, conference proceedings and book chapters were excluded from the review. Only papers published in open-access journals were included. According to the non-redundancy criterion and the abstracts' relevance, the papers were then further filtered. The chosen papers were then combined to answer the research questions.

Method of data analysis

Recent advancements in bibliometric software have made it possible to analyze specific scientific domains, themes, or research issues with greater precision. These software tools utilize mathematical and statistical methods - such as word frequency analysis, co-citation analysis, bibliographic coupling and keyword co-occurrence - to process bibliometric data (30). *Bibliometrix*, an open-source tool developed in the R programming language, enables comprehensive scientific mapping. The software also facilitates the construction of collaborative networks by identifying co-authorship patterns across publications (31). Table 1 presents the inclusion and exclusion criteria used for the systematic literature review.

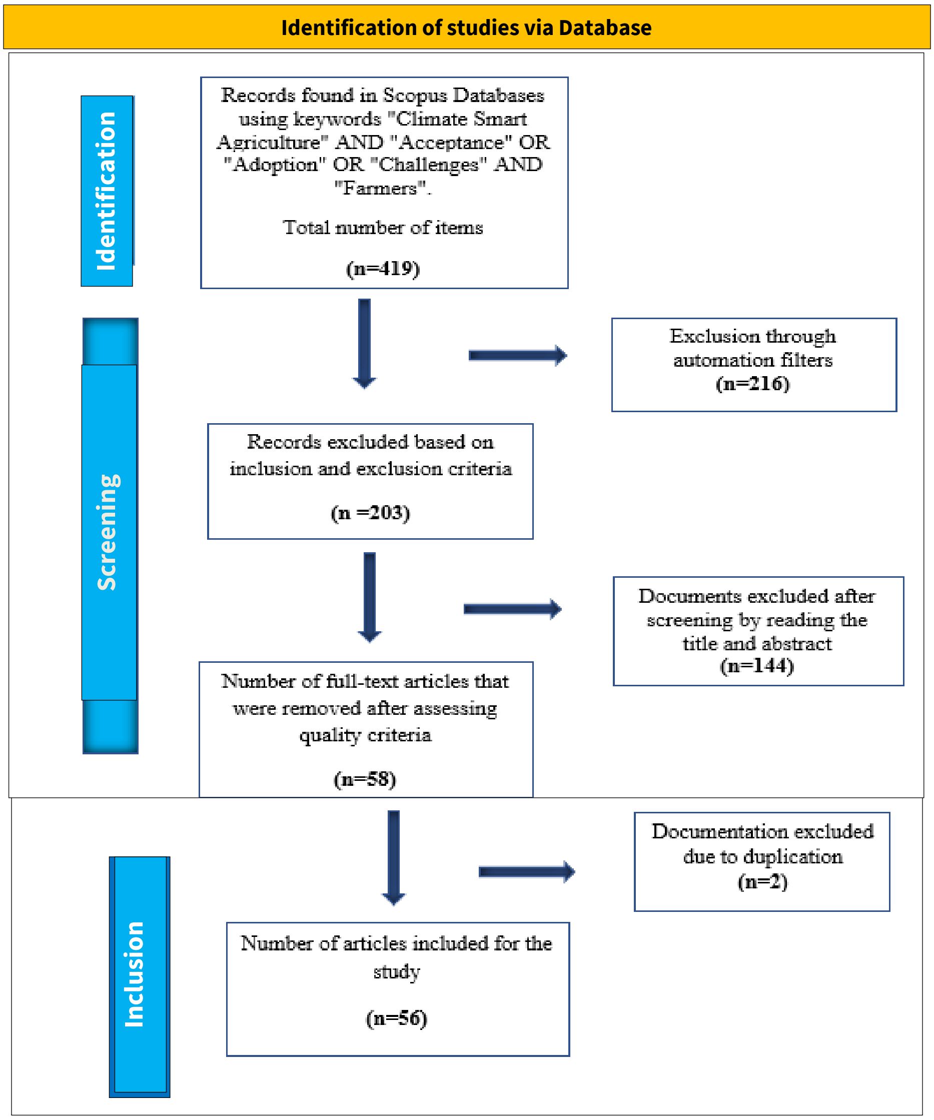

Fig. 2. The PRISMA flow chart illustrates the document screening process.

Table 1. Inclusion and exclusion criteria for systematic literature review

Criteria	Inclusion	Exclusion
Initial Criteria		
Literature Type	Research articles, Review articles and abstracts with keywords	Book chapters, Conference papers
Timeline	2019-2024	<2019
Subject Area	Social sciences, Environmental Science, Agricultural and Biological Sciences	Engineering, Medicine, Biochemistry, Genetics and Molecular Biology, Earth and Planetary Sciences, Chemistry, Physics, Pharmacology, Toxicology.
Access Type	Open source	Restricted access
Language	English	Non-English
Publication Stage	Final	Press
Screening		
Title and Abstract	Existence of predefined keywords in the title, abstract or keywords in part of the paper. Included articles that studied trends, acceptance and adoption barriers related to climate-smart technologies among farmers.	
Full Text	Included determinants of acceptance and adoption barriers related to climate-smart technologies among farmers, economic development and sustainability.	

Bibliometric review

The fifty- six papers obtained after applying the inclusion and exclusion criteria were subjected to bibliometric analysis. This analysis of 56 documents from 2020 to 2024 reveals significant research activity, sourced from 34 journals and books. Despite the relatively recent emergence of this body of literature, the annual growth rate of publications stands at 19.81%, indicating a notable increase in scholarly interest during the period. The average age of the documents is 1.4 years, with each receiving an average of 14.23 citations, underscoring their relevance and impact. Collectively, the studies cited a total of 3,535 references, reflecting a robust and extensive literature base.

Thematic analysis identified 152 "Keywords Plus" and 205 "Author's Keywords," reflecting a diverse range of research topics and thematic diversity. Collaboration is a defining feature of this research domain, with 226 authors contributing and an average of 4.23 co-authors per document. Notably, international collaboration is significant, with 47.37% of the papers involving authors from multiple countries. All 56 documents are peer-reviewed articles, affirming the academic rigor and scholarly quality of the research. Table 2 provides detailed information about the articles selected for review.

Table 2. Information about articles selected for review

Information Details	Values
Timespan	2020- 2024
Sources (Journals, Books, etc.,)	34
Documents	56
Annual Growth Rate %	19.81
Document Average Age	1.4
Average citations per doc	14.23
References	3535
DOCUMENT CONTENTS	
Keywords Plus (ID)	152
Author's Keywords (DE)	205
AUTHORS	
Authors	226
Authors of single-authored docs	1
AUTHORS COLLABORATION	
Single-authored docs	1
Co-Authors per Doc	4.23
International co-authorships %	47.37
DOCUMENT TYPES	
article	56

Results

Annual scientific production of articles related to climate smart agriculture

Fig. 3, illustrates the annual scientific production of CSA literatures in terms of the number of articles published between the years 2020 and 2024. In 2020, approximately seven articles were published, with a slight increase to around eight articles in 2021. This upward trend continued modestly in 2022, reaching nine publications. However, 2023 witnessed a minor decline, with the number of publications dropping back to approximately seven. A significant surge occurred in 2024, with the number of articles raising sharply to around 21-nearly three times the output of the previous year. This notable increase may indicate growing interest in the CSA research domain or reflect enhanced publication opportunities, possibly driven by new funding avenues or expanded international collaboration initiatives.

Country production over time

Fig. 4, presents a comparative analysis of the number of articles produced by various countries between 2020 to 2024. Notably, China and Kenya exhibit the most significant growth in article production over this period, with China showing a substantial increase in 2023 and maintaining a high level through 2024. India and the USA also show consistent growth, although the USA starts its data from 2021, perhaps indicating a later initiation of the study in this field. The Netherlands and Ethiopia exhibit more moderate increases. While the Netherlands' production output stabilizes after 2023, while Ethiopia, after an initial period of stagnation in 2020 and 2021, shows a noticeable upward trend from 2022 onwards, indicating a possible shift in research or policy focus that started to yield increased outputs in subsequent years.

Most relevant sources of journals

Table 3, highlights the distribution of research articles across various journals, with Mitigation and Adaptation Strategies for Global Change contributing the most (5 articles), followed by Sustainability (Switzerland) (4 articles). Several journals, including Cogent Food and Agriculture, Frontiers in Sustainable Food Systems and Smart Agricultural Technology, contributed 3 articles each, focusing on sustainability, food systems and climate strategies. Other notable journals such as Agronomy, Indian Journal of Extension Education and International Journal of Environmental Research and Public Health contributed 2 articles. A wide range of other journals contributed 1 article each, underscoring the interdisciplinary and diverse nature of the research field, with a strong focus on climate change, agricultural technology and sustainability

Most cited countries

Table 4, presents the total citations and average citations per article across various countries. South Africa ranks highest with 127 total citations and an impressive average of 42.3 citations per article, followed by the Netherlands with 117 total citations

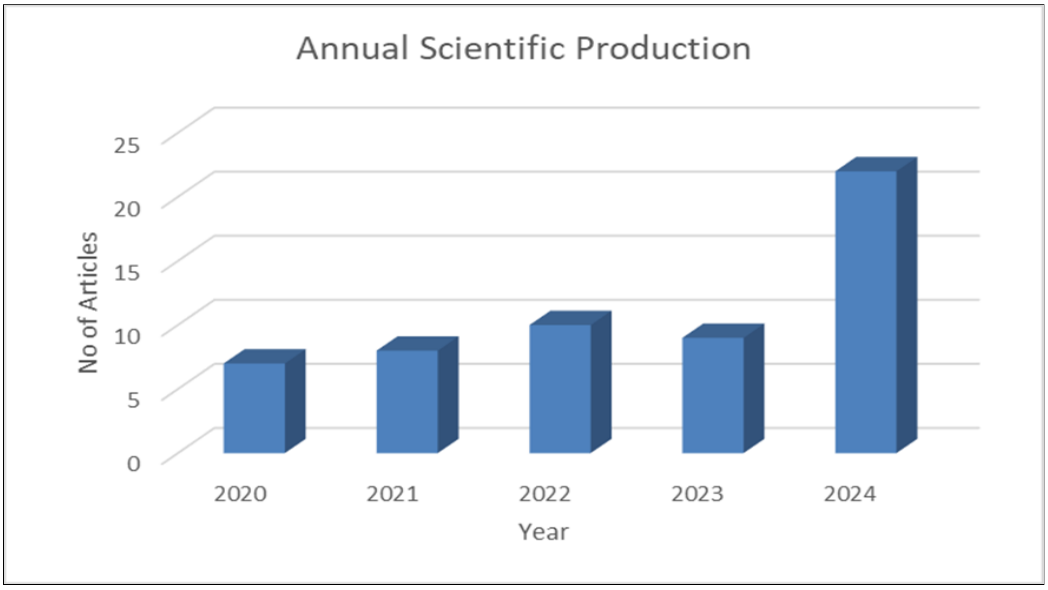

Fig. 3. Annual scientific production of articles.

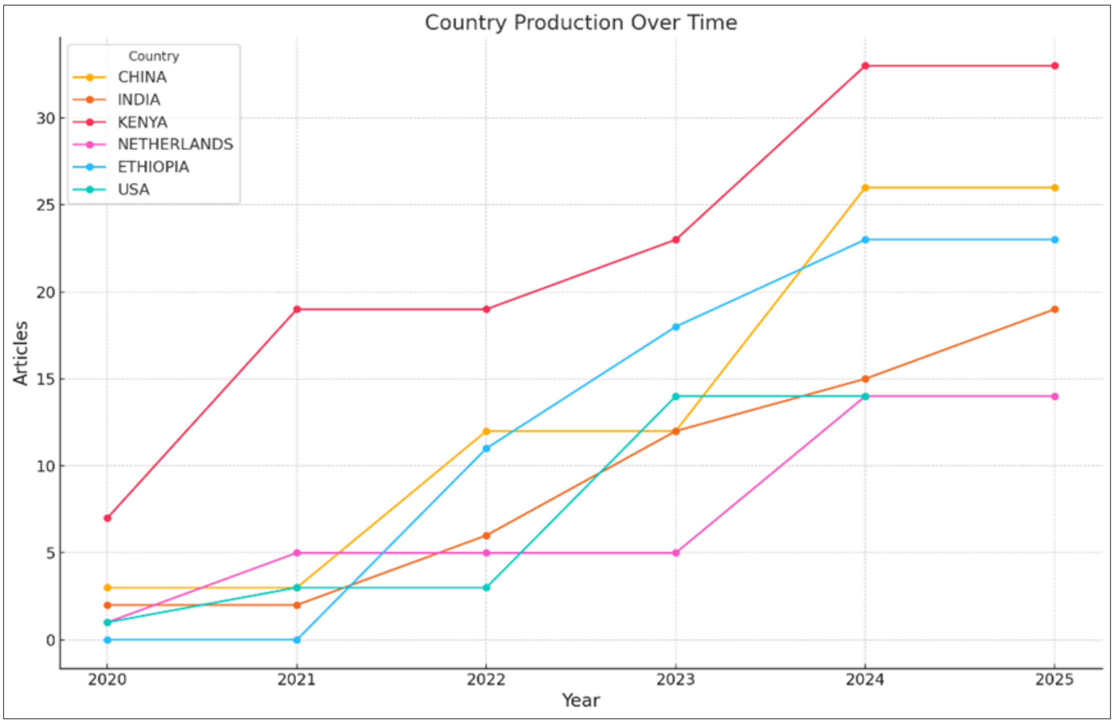

Fig. 4. Annual scientific production of articles.

Table 3. Most relevant sources of journals related to CSA

Sources	No of Articles
Mitigation and Adaptation Strategies for Global Change	5
Sustainability (Switzerland)	4
Cogent Food and Agriculture	3
Frontiers in Sustainable Food Systems	3
International Journal of Climate Change Strategies and Management	3
Smart Agricultural Technology	3
Agricultural Systems	2
Agronomy	2
Environmental Challenges	2
Indian Journal of Extension Education	2
International Journal Of Environmental Research And Public Health	2
Journal of Agriculture And Food Research	2
Sustainability (Switzerland)	2
African Journal of Food, Agriculture, Nutrition and Development	1
Agricultural Science Digest	1
Asian Journal of Agriculture and Rural Development	1
Climate Risk Management	1
Climate Services	1

Table 4. Most cited countries in the year of 2020- 2024

Country	Total Citation (TC)	Average Article Citations
South Africa	127	42.3
Netherlands	117	23.4
Kenya	84	14
China	76	19
Vietnam	61	30.5
Finland	57	57
India	56	8
Ethiopia	55	9.2
United Kingdom	49	24.5
Ghana	43	21.5
Mali	13	13
USA	12	3
New Zealand	11	3.7
Benin	5	5
Japan	2	2
Zimbabwe	2	2
Belgium	1	1

and an average of 23.4 per article. Finland stands out with a high average of 56 citations per article despite a lower total citation count (62). Countries such as Kenya, China and Vietnam also show significant contributions, with Vietnam having a particularly high average of 30.5 citations per article. While countries like India and Ethiopia contribute a fair number of total citations, their average article citations are comparatively lower, at 8 and 9.2 respectively. Conversely, the USA, New Zealand and several other countries exhibit lower total and average citations. This data reflects the varying levels of influence and citation impact of research across different nations, with a few countries achieving high citation averages with fewer total publications.

Trend topics in adoption and constraints of CSA

Fig. 5 presents a trend analysis of key research topics over time, offering an overview of topic frequency and their respective median publication years within the field of agriculture. The topics examined include "agriculture," "crop production," "climate change," "smallholder," "agricultural practice," "agricultural technology " and "climate effect." The literature had an increased focus on climate change and climate effects respectively (32, 33). The focus on agricultural technology was asserted by a study titled "Promoting the adoption of climate-smart agricultural technologies among maize farmers in Ghana: using digital advisory services" (34).

The bar graph represents the frequency of each research topic, while the line graph shows the median year for each. Among the topics, "climate change" has the highest frequency, indicating it is the most commonly discussed subject in the dataset, possibly due to its increasing relevance in recent years. Topics such as " smallholder" and "agricultural practice" also have higher frequency levels, reflecting the importance of these areas in current research or policy discussions. The median year line suggests a progressive increase in interest over time, with recent years seeing a focus on topics like "smallholder" and "climate change," hinting at a trend towards addressing the impacts of climate change and the role of smallholders in sustainable agricultural practices.

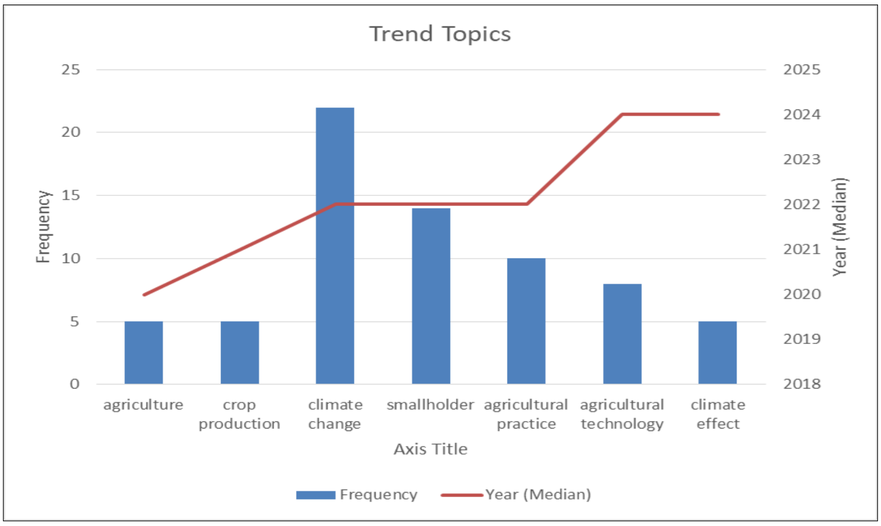

Fig. 5. Trend topics in adoption and constraints of CSA.

Overall Fig. 5, highlights the growing academic and policy attention towards climate-related agricultural topics. This trend likely mirrors broader societal and environmental shifts, compelling the agricultural sector to adopt more sustainable and climate-resilient practices. The relatively recent median publication years imply that research in these domains is current, dynamic and responsive to global challenges related to climate change and food security.

Keyword Co-occurrence in CSA

Fig. 6, represents a keyword co-occurrence network, illustrating the interconnectedness of various research themes. The keyword "climate change" stands out as the most prominent, occupying a central position within the network, highlighting its widespread relevance across multiple topics. Keywords such as smallholder, agricultural practice, agricultural technology and technology adoption are closely linked to climate change, demonstrating the interplay between climate concerns and agricultural innovations. Other key terms like climate effect and perception are also well connected, suggesting that the perception of climate impacts is an important area of research.

The network structure reveals clusters of keywords representing different thematic areas, with dense connections between terms, indicating highly interrelated fields of study. The co-occurrence of these terms emphasizes a strong focus on sustainability, climate resilience and technological solutions in agriculture. Overall, the image reflects the centrality of climate-related issues in agricultural research and the growing emphasis on technological adoption and practices that support adaptation and sustainability.

Word frequency over time

Fig. 7 illustrates the changing trends in the usage of specific terms related to agricultural and climate research from 2020 to 2024. "Climate Change" emerges as the most frequently referenced term, reflecting the growing global emphasis on environmental sustainability and its implications on agriculture. The prominence of terms such as "Smallholder," "Agricultural Practice," and "Technology Adoption" suggests a significant focus on the challenges and advancements experienced by small-scale farmers in adopting innovative practices and technologies.

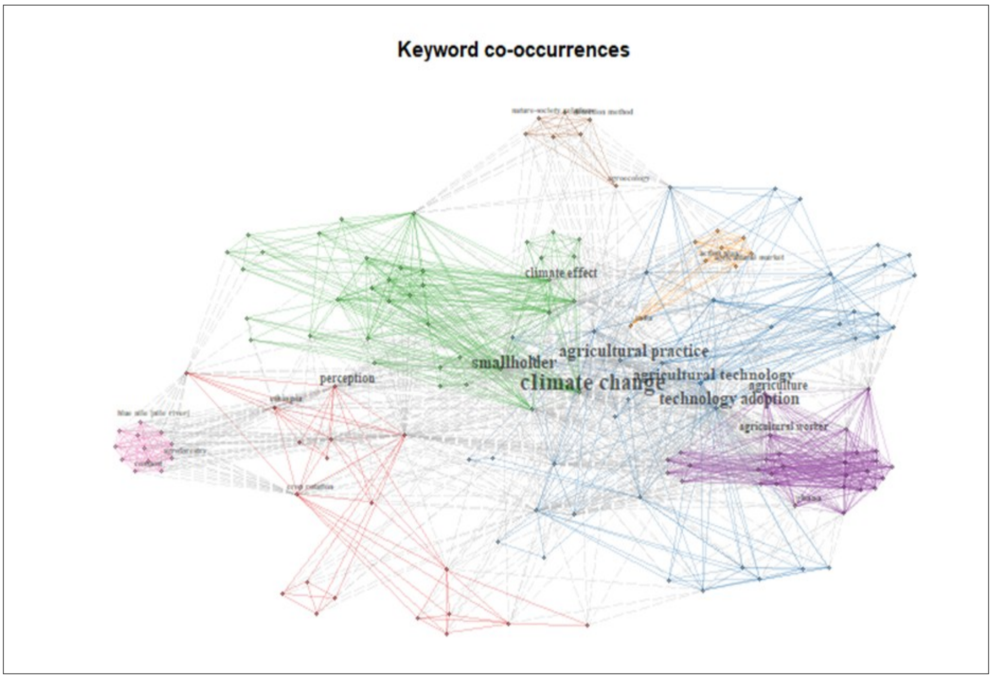

Fig. 6. Keywords co-occurrences interconnecting research themes.

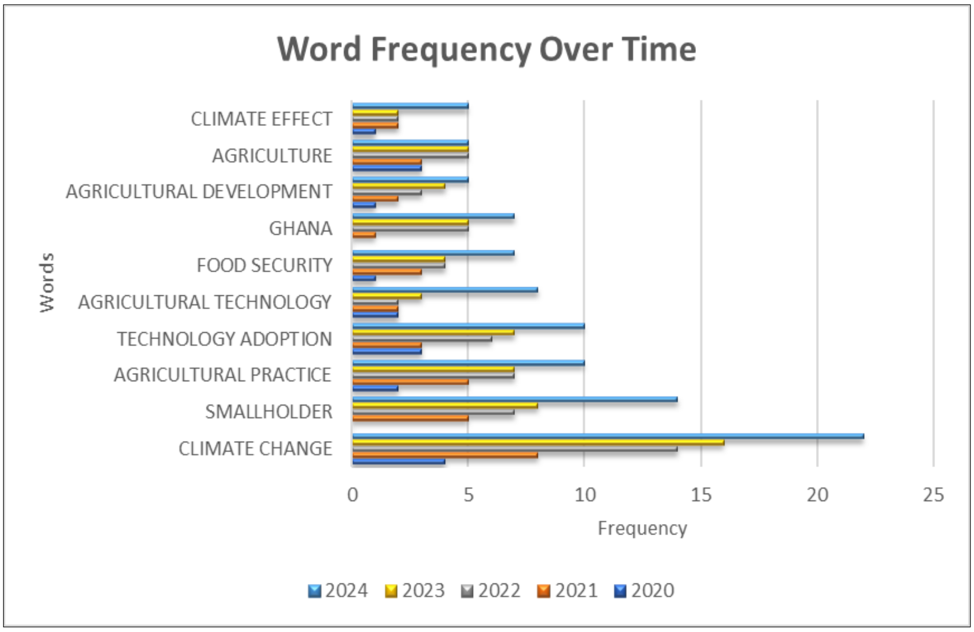

Fig. 7. Frequency of words over the period 2020- 2024.

The rising frequency of "Agricultural Technology" and "Food Security" highlights the increasing acknowledgment of technological interventions to ensure sustainable food systems. The appearance of terms like "Agricultural development" and "Ghana" points to region-specific studies, particularly those centered on agricultural advancements in Africa. A modest but steady mention of "Climate effect" signifies the consistent exploration of climate impact on agriculture.

Overall, the data reflects a dynamic research landscape, evolving to address the intersection of climate change, technological innovation and socio-economic factors in agriculture. It highlights the scientific community's shifting priorities toward building resilient and sustainable agricultural practices over time.

Finding and Discussion

The adoption of CSA technologies is increasingly recognized as crucial for enhancing resilience, productivity and sustainability in global agricultural systems, particularly in light of the growing impacts of climate change (35). These technologies provide pathways to mitigate climate-related risks, improve crop yields and promote sustainable farming practices, making them indispensable for smallholder farmers, who are often the most vulnerable to climate impacts (36). Numerous studies have underscored the complex dynamics, including barriers and enablers, that influence CSA adoption across diverse regions and agricultural systems (37).

In Southeast Nigeria, cooperatives and extension services play a pivotal role in raising awareness about CSA practices, with enhanced support in areas such as gender equity, education and access to credit being crucial (38). The study by (39) underscores the significance of CSA interventions such as irrigation and crop insurance in improving household incomes, while advocating for better credit access and continuous farmer education. In the European context, stakeholder collaboration, economic incentives, enabling policies and technological advancements have been identified as key drivers of CSA adoption across food supply chains, offering a replicable model for integrating CSA into broader agricultural frameworks (40). Financial incentives have been recognized as a critical factor in promoting the adoption of Climate-Smart Agriculture (CSA). In Malaysia, both financial and non-financial incentives are deemed essential for encouraging CSA uptake, despite challenges such as high implementation costs and limited institutional support (41). (41), In Uganda, smallholder coffee farmers who demonstrate entrepreneurial mindset and positive attitudes are more likely to adopt and maintain CSA practices (42). Similarly, findings from Vietnam indicate that education, household income and supportive policies play pivotal roles in enabling adoption, although limited capital and insufficient technical assistance remain significant barriers (43).

Demographic and socio-economic factors, including gender, age, land size and financial resources, consistently emerge as influential determinants in CSA adoption. Studies from Ethiopia and Ghana emphasized the importance of tailored strategies that account for these variables (34, 44). Farmers in Taiwan, possessing greater knowledge and a stronger perception of the value of smart agricultural technologies are more inclined to adopt CSA, underscoring the need for targeted educational strategies (45). Furthermore, digital solutions, such as Digital Advisory Services (DAS), have been shown to facilitate CSA adoption by providing real-time information and technical advice.

Despite these benefits, numerous constraints limit the widespread adoption of CSA practices. Economic barriers are among the most significant, including high initial investment costs, ongoing financial requirements and limited credit access. In non-climate-smart villages, technical challenges-such as lack of awareness-persist, whereas in climate-smart villages, economic concerns like elevated production costs and substantial upfront investments are more prevalent (46) . Additional limiting factors such as age, educational background, access to credit and off-farm income, are identified as substantial constraints, which can hinder the farmer's ability to invest in CSA-related inputs and technologies (47, 32). In Ethiopia, gender-specific challenges and large household sizes have been found to significantly hinder CSA uptake (48). The author emphasized that in Pakistan, smallholder farmers face significant financial and procedural challenges due to limited institutional support, further complicating CSA adoption (49).

Socioeconomic and demographic factors also play a critical role in influencing CSA adoption. Younger farmers, for instance, are more receptive to new practices, while older farmers often prefer to adhere to traditional methods (50). Gender disparities are prominent in rural communities, where women often lack access to essential resources like land, credit and extension services. Enhancing women's accesses to financial and institutional support could significantly enhance CSA adoption rates, given their essential roles in farm management and food production (38, 39). In Kenya, both gender and farm income had been identified as influential factors, highlighting the importance of empowering women and increasing household income to promote greater CSA uptake (69).

Institutional support deficiencies exacerbate these socio-economic barriers. Rice farming systems in Mali face challenges, such as limited input availability, high seedling costs, labor shortages and restricted land access for women and youth (51). Similarly, limited access to extension services, credit and subsidies have been identified as barriers to CSA adoption in Odisha, India (52). The insufficient technical capacity of extension services has also been found to hinder knowledge transfer (53). In this context, digital tools like DAS could complement traditional extension by providing timely information directly to farmers (34).

Environmental and climate-specific factors also impact CSA feasibility. Climate variability, extreme weather events and resource scarcity pose significant challenges to implementing practices like rain-fed irrigation and soil conservation. In drought-prone areas, limited water resources hinder irrigation, which is essential for climate resilience (54). Adaptive strategies that incorporate CSA with traditional agricultural knowledge can enhance resilience by aligning practices with local farming systems and cultural contexts (40, 42). Additionally, environmental challenges like land degradation and water shortages in remote regions further complicate CSA adoption (55). Restrictive market conditions and the emergence of new pests create additional barriers to uptake (56).

Policy inconsistencies and governance issues also impede CSA adoption. While policies that incentivize sustainable practices through financial subsidies and resource access facilitate adoption, fragmented support systems and weak enforcement undermine these efforts. The need for coherent, consistent policies to sustain CSA support, while entrenched traditional practices and inadequate state resources limit CSA adoption in India (57-59). Consistent policy frameworks that provide subsidies for CSA inputs, tax reductions and crop insurance schemes could lower costs and reduce risks associated with CSA adoption (60). Governance challenges also hinder CSA uptake. In the U.S., farmers struggle with unclear program guidelines and inconsistent support, this limits their participation in CSA programs (61).

Cultural factors also play a significant role in CSA adoption, as community norms and traditional practices affect farmers' openness to new technologies. In some areas, farmers are reluctant to abandon conventional methods, especially if they have proven effective historically (33). A participatory approach that involves farmers in decision-making and respects indigenous knowledge can help build trust and demonstrate CSA's tangible benefits, fostering positive attitudes toward adoption (62, 43). Fostering an entrepreneurial mindset among farmers could help them view CSA as a long-term investment, motivating sustained adoption (42, 43). In urban settings, cultural attachments and limited access to vital resources like arable land and water pose challenges for CSA adoption (63).

Resource scarcity further complicates adoption, particularly in areas with limited access to essential agricultural inputs like seeds, fertilizers and water (56). For instance, water shortages severely restrict CSA practices requiring irrigation (64). The identified resource limitations, infrastructure deficiencies and inconsistent climate awareness among farmers as barriers to CSA (65). Addressing these issues requires investment in infrastructure, such as irrigation and storage facilities, along with sustainable resource management that promotes efficient use (55).

Digital technology and improves access to information can significantly support the adoption of CSA by providing farmers with real-time information on climate conditions, market trends and best agricultural practices (66). Tools such as DAS, mobile applications and online platforms have been effective in reaching farmers in remote areas (34, 67). However, limited digital literacy and infrastructure remain barriers, as not all farmers have the skills or resources to fully utilize these tools. Expanding rural internet connectivity and investing in digital literacy programs are crucial steps to empower farmers to integrate CSA practices (68).

To address the challenges hindering the adoption of CSA technologies, several targeted interventions are essential. Financial constraints are among the primary challenges, with high costs of inputs, infrastructure and labor requirements deterring many farmers from implementing CSA practices (69). Expanding credit access and providing affordable financing options, such as low-interest loans, subsidies and tax incentives, can empower farmers to make the necessary investments for CSA adoption (37, 60). Strengthening extension services and enhancing farmer education are also critical, as they provide the knowledge and technical support farmers need to implement CSA practices effectively (70). Improved farmer-to-extension agent ratios, coupled with digital tools like DAS, can extend the reach of extension services, especially in remote areas, thus enhancing farmers' decision-making and adaptability to climate risks (53, 71). Digital solutions also enable real-time information sharing, giving farmers access to updates on climate conditions, pest control and market trends that are vital for CSA's success (64).

Moreover, it is essential to tailor CSA strategies to socio-demographic factors such as age, education, gender and household income, which significantly influence adoption rates (72). Programs targeting younger farmers who may be more receptive to new practices should also account for the needs of older farmers who adhere to traditional methods (73). Gender-sensitive interventions are essential in rural communities where women often lack access to resources like land and credit, despite their critical role in farm management and food production (74). Empowering women through targeted financial support and access to extension services could increase CSA participation (34, 39).

Enhanced institutional support and improved infrastructure are also crucial for creating an enabling environment for CSA adoption. Investments in infrastructure, such as roads and market facilities, can improve market access for farmers, stabilize their incomes and increase their capacity to invest in CSA technologies. Farmer cooperatives and associations can further strengthen collective bargaining power, reduce input costs and improve market access, thus facilitating CSA implementation (51).

Region-specific and environmentally adaptive approaches are essential for CSA sustainability, given environmental variability and the need for practices tail or ed to local conditions (75). For instance, water-efficient irrigation practices are particularly critical in drought-prone areas, where water scarcity limits adoption. Combining CSA with traditional agricultural knowledge can enhance resilience by aligning CSA practices with local farming methods and cultural contexts, fostering acceptance and sustainability(54,40).

Consistent policy frameworks and supportive incentives, such as subsidies, tax breaks and insurance schemes, are vital for promoting CSA adoption by reducing associated costs and providing a safety net for farmers (76). Coherent policies that prioritize CSA adoption can help farmers overcome financial and institutional barriers, allowing them to invest confidently in CSA practices (57-60). Addressing these complex barriers through integrated financial assistance, policy support, extension services and tailored educational strategies can enable widespread CSA adoption and foster resilient, sustainable farming systems globally (77).

Conclusion

CSA offers a transformative approach to enhancing agricultural resilience, productivity and sustainability in response to climate change. However, its adoption remains uneven due to socio-economic, institutional and environmental constraints. Addressing these barriers requires integrated strategies, including financial incentives, enhanced extension services, gender-sensitive interventions and strong institutional support. Investments in infrastructure, market access and localized solutions can further facilitate adoption. Strengthening community networks and farmer cooperatives can foster knowledge-sharing and collective action. By addressing these challenges holistically, CSA can become a cornerstone of sustainable agriculture, ensuring long-term food security and climate resilience.

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Authors' contributions

VS Conducted an extensive literature review, synthesized key concepts and drafted the manuscript. NA Provided guidance on the conceptual framework, ensured the integrity of the review process and approved the final manuscript. PPM Contributed to refining ideas, critically reviewed the manuscript and facilitated access to relevant resources. MRL Assisted in organizing content, revising the manuscript and ensuring clarity and coherence. RPS Conducted statistical analyses of secondary data, contributed to summarizing findings and enhanced the quality of the manuscript through revisions.

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