Environment, Development and Sustainability
https://doi.org/10.1007/s10668-025-06782-4

REVIEW ARTICLE

Bridging the gap between natural and social sciences: a bibliometric review of climate-smart agriculture-challenges and opportunities

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Received: 22 December 2024 / Accepted: 11 August 2025

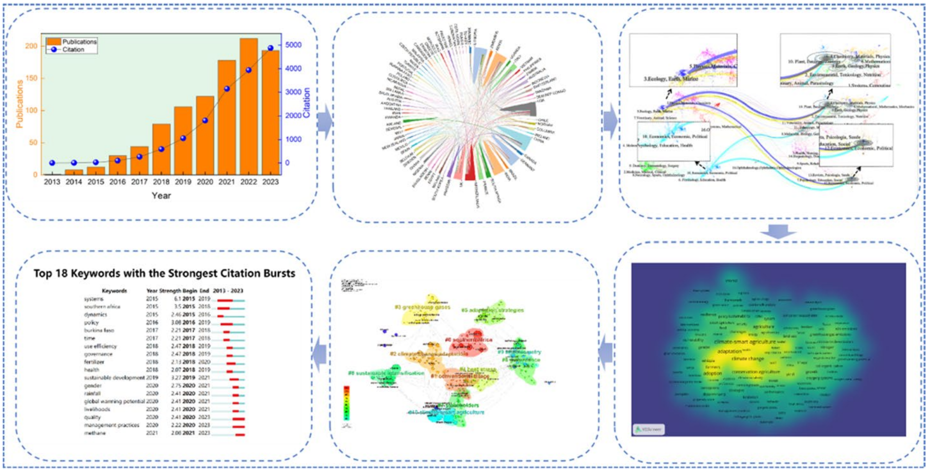
Abstract

Global climate change puts pressure on agricultural systems, which in turn exacerbate global warming. Climate-smart agriculture (CSA) aims to address the dual challenges by enhancing productivity, resilience, and mitigation. However, existing research remains largely isolated within either natural or social sciences, limiting its potential to address complex agricultural issues. This review bridges the gap with a bibliometric analysis of 997 Web of Science documents (2013–2023) using CiteSpace and VOSviewer. It aims to reveal cross-disciplinary challenges and opportunities by analyzing keywords clusters and citation bursts, based on publication trends, categories, journals, authors, affiliations, and geographic distributions. The findings include: (1) From horizontal keywords clusters: CSA adoption in Southern Africa cluster is hindered by multiple barriers, while inclusive and collaborative approach offers opportunities. No-tillage cluster faces inconsistent yield impacts. Climate adaptation struggles with resource, governance, and continuity challenges while pro-poor economic integration offers opportunities. Greenhouse gas cluster presents contradictory findings with opportunities through studying in mechanisms driving GHG fluxes, and the challenges and opportunities in heat stress cluster are in balancing temperature extremes. (2) From temporal keywords citation bursts: early research focus on policy integration and agricultural system dynamics with challenges in cost-benefit uncertainties and policy scalability, while later on, incorporating women into CSA design provides key opportunities for inclusive development. In the latest stage, methane emissions from paddy fields have become a major issue. These insights lay a foundation for addressing the intertwined challenges of climate change and agricultural sustainability.

Extended author information available on the last page of the article

Published online: 31 August 2025

Graphical abstract



Keywords Climate-smart agriculture · Systematic review · Climate change · Adaptation · Greenhouse gases

1 Introduction

Global climate change, marked by rising temperatures, shifting precipitation patterns, and intensified extreme weather events, has emerged as a critical threat to global agricultural systems (Getnet et al., 2023; Mabitsela et al., 2023; Roberts & Florentine, 2024). Agriculture paradoxically stands as both a victim and a contributor to this crisis (Abegunde et al., 2020). Higher temperatures further intensify drought stress and accelerate crop development, shortening the growing period and disrupting grain filling, which increases yield variability and the risk of crop failure (Rezaei et al., 2023). Climate change accounts for approximately one-third (32–39%) of observed yield variability worldwide (Ray et al., 2015). At the same time, agriculture significantly contributes to global warming. Excessive applications of nitrogen-fertilizers and enteric fermentation from livestock are major sources of agricultural global greenhouse gas (GHG) emissions (He et al., 2023; Kabange et al., 2023; Qian et al., 2023). Collectively, agriculture, forestry, and other land use account for approximately 24% of total global GHG emissions (IPCC, 2023). Therefore, the interplay between agriculture and climate change necessitates innovative and adaptive agricultural practices to mitigate adverse impacts while adapting to ongoing environmental shifts (Autio et al., 2021; FAO, 2013; Sardar et al., 2021).

To address these pressing issues, the Food and Agriculture Organization (FAO) defined and presented Climate-Smart Agriculture (CSA), offering a transformative framework to mitigate the impact of climate change on agriculture in 2010 (FAO, 2013). CSA has three objectives: increasing agriculture productivity and farmers' incomes, building resilience to climate change; and reducing greenhouse gas emissions. By combining economic, social, and environmental aspects, the FAO hopes to achieve sustainable development goals through this agricultural paradigm (FAO, 2013; IPCC, 2023). As CSA has gained global recognition, regional and international efforts have increasingly translated CSA principles into concrete policy frameworks. The Association of Southeast Asian Nations (ASEAN) Regional Guidelines for Promoting CSA Practices provide member countries with practical tools and principles to identify, prioritize, and scale up CSA practices for greater productivity and climate resilience (Labios et al., 2021). The European Deforestation Regulation (Regulation (EU) 2023/1115) advances the mitigation goal of CSA by restricting the import of agricultural commodities linked to deforestation, thereby addressing land-use change emissions and promoting climate-responsible supply chains (European Union, 2023). These initiatives reflect that CSA is a holistic approach to transforming agricultural systems under climate change.

Technically, agricultural practices are considered as CSA if they enhance productivity or optimize resource-use effectiveness, reduce farmers' vulnerability to climate change, lower GHG emissions, and increase carbon stock (Neufeldt et al., 2013). For example, using stress-tolerant varieties can stabilize and improve farm output even under adverse conditions (Nyagumbo et al., 2022; Radeny et al., 2022). Increased farm production improves farmers' resilience to extreme weather events (Musara et al., 2022; Waaswa et al., 2021). Furthermore, practices such as minimum tillage, efficient crop residue management, and balanced nutrient application enhance carbon sequestration in agroecosystems and improve resource-use effectiveness, thereby reducing GHG emissions without compromising yield (Musafiri et al., 2022; Nantongo et al., 2023; Ngoma, 2018; Teklu et al., 2023b). Overall, these strategies contribute to more sustainable and resilient agricultural systems.

Numerous studies have examined CSA, leading to several qualitative reviews on the subject. Morkunas & Balezentis (2022) reported CSA research topics involved global food security, challenges at the micro-level in adopting CSA practices, macro-level perspectives on government roles and initiatives in promoting CSA, methodological approaches to assessing and implementing CSA practices, empirical evaluations of CSA practice effectiveness, and scenario modeling. Mizik (2021) conducted a comprehensive review of CSA implementation on small-scale farms, summarizing its benefits, motivating factors, and major constraints in the adoption process from 30 articles using the method of PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). Mutengwa et al. (2023) provided an overview of CSA and food security in southern Africa, emphasizing the vulnerability of smallholder agriculture to climate change. They highlighted CSA as a response to the global climate challenge, noting the significant status of smallholder agriculture and the various challenges in implementing and promoting CSA practices. Brouziyne et al. (2023) reviewed the impacts of CSA practices to GHG mitigation in the agriculture sector and revealed the inadequate establishment of CSA framework for GHG sequestration through an analysis of 11 articles with the method of PRISMA.

While the previous qualitative review papers have summarized research on CSA, systematic bibliometric analyses that combine quantitative and qualitative approaches remain limited. Notably, most prior qualitative reviews have been conducted within the isolated domains of social or natural science, each focusing on specific aspects of CSA such as policy, farmer behavior, or biophysical impacts. This disciplinary separation has led to a fragmented understanding of CSA, constraining its potential to deliver adaptive agricultural productivity and climate resilience. A systematic bibliometric review not only integrates natural and social sciences in CSA research but also provides a structured framework for guiding future research. Natural science, by analyzing biophysical and chemical processes, offers the empirical foundation for scientific decision-making, while social science, by examining human behavior, policy, and economic constraints, directs the application and relevance of scientific findings. The dynamic interplay between these disciplines ensures that research remains both scientifically rigorous and practically applicable, aligning CSA strategies with farmers' needs and broader sustainability goals. This integrated approach ultimately enhances the feasibility and scalability of CSA practices, advancing sustainable agriculture and long-term environmental sustainability.

2 Methodology

All literature was retrieved from the Web of Science Core Collection database (Science Citation Index Expanded and Social Science Citation Index) on 16th March 2024, given this database's reliability, comprehensiveness, and prevalence. The search query, TS = "(climate-smart agriculture) or (climate-smart agricultural)" were used to collect literature about the topic from 2013 to 2023, as no publications explicitly mentioned CSA before 2013. The document type was restricted to "Article", and after applying the language filter for English, a total of 997 documents were obtained for bibliometric analysis. This study examines publications, authors, institutional affiliations, journals, citations, and keywords. Visualization was achieved using bibliometric tools such as CiteSpace (version 6.3.R1) and VOSviewer (version 1.6.20). Figures present visual representations of institutions, authors, and keywords, with nodes representing these entities and node size indicating publication numbers. Lines between nodes denote connections, with line thickness reflecting connection frequency. A schematic overview of this study is shown in Fig. 1.

3 Results and discussion

3.1 Analysis of publications and research categories

Figure 2(a) illustrates number of publications and citations related to CSA from 2013 to 2023. The evolution can be segmented into two phases. During the initial phase, from 2013 to 2017, a limited number of papers were published annually, indicating limited attention and interest in the topic, possibly because CSA was only defined in 2010. In contrast, the second phrase, from 2018 to 2023, experienced a substantial increase in both publications and citations. This indicates the increasing attention and research interest in CSA, possibly driven by international policy emphasis, including the World Bank's $200 billion Climate Action Plan (World Bank, 2018), FAO's recognition of CSA's role in achieving sustainable development goals (FAO, 2019) and various policy initiatives implemented across different countries. The average number of citations per document is 16.86, with a total of 11,607 references. In Fig. 2(b), Environmental Sciences emerges as the dominant category, comprising 293 articles, which represents 29.36% of the total 997 articles. Following is Environmental Studies with 180 articles (18.04%), Agronomy with 138 articles (13.83%), Green Sustainable Scienc Technology with 119 articles (11.92%), Agriculture Multidisciplinary with 112 articles (11.22%). The total percentage exceds 100% because each journal can

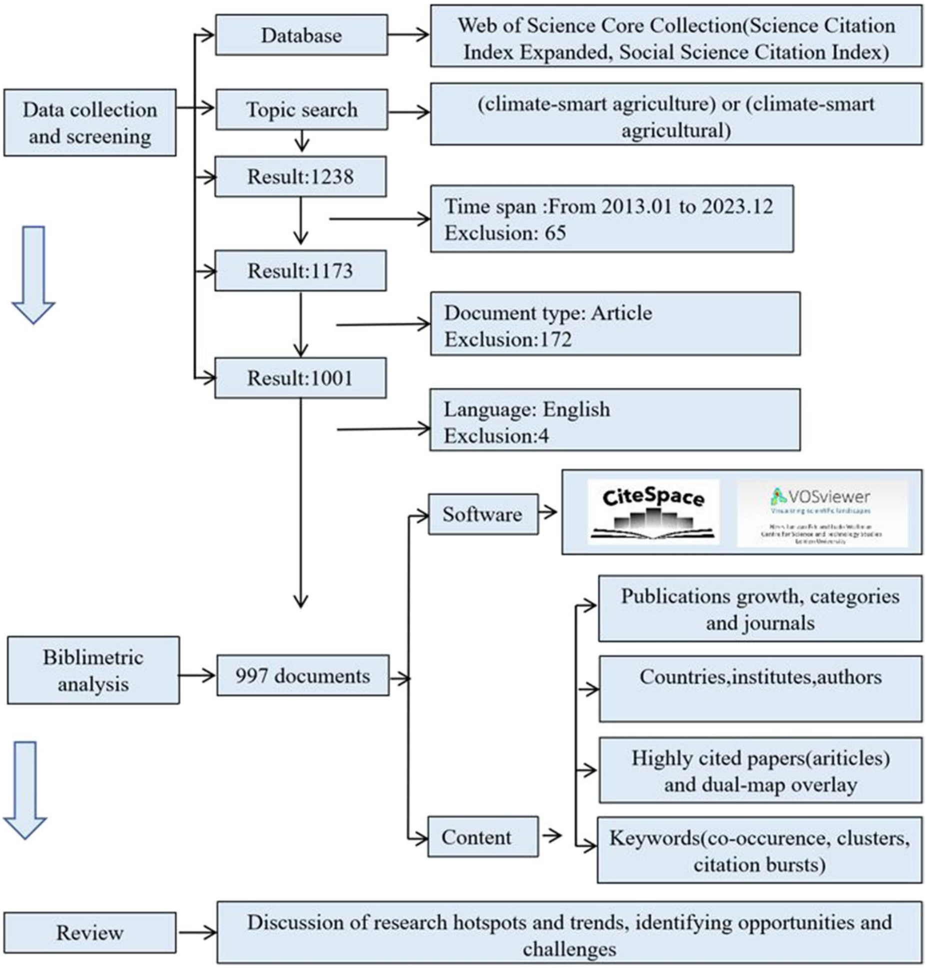
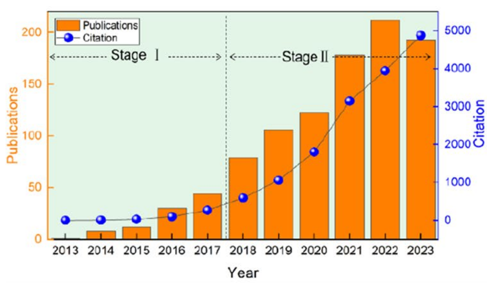
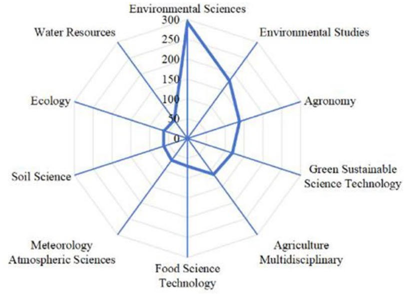


Fig. 1 A schematic overview of this study

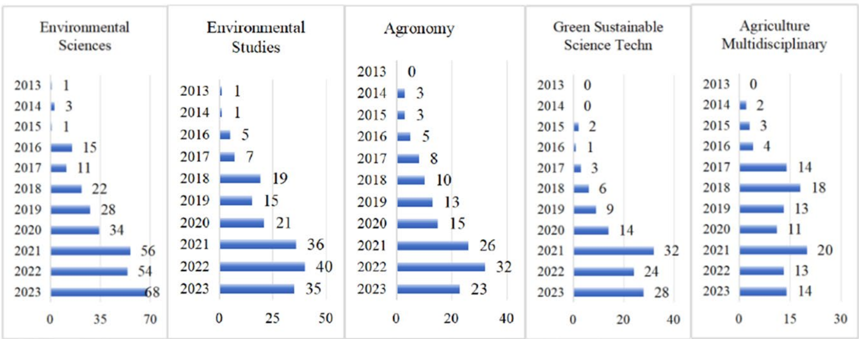
be categorized under multiple categories simultaneously. This overlap reflects the interdisciplinary nature of CSA research. The leading 5 categories can be ascribed to that CSA is framed within the context of global climate change and aims to reduce carbon emissions in the agricultural sector without compromising economic goals. Figure 2(c) displays the publication trends of the top five categories, showing a notable increase in attention, particularly after 2018. Agriculture Multidisciplinary reached a plateau after 2017, whereas the other four leading categories leveled off after 2021. This suggests that the number of CSA-related studies is unlikely to experience substantial growth, although Environmental Sciences may continue its sustained upward trend in publication output.



(a) Publications and citations trends from 2013 to 2023



(b) Distribution of categories from 2013 to 2023



(c) The publication trends of the top 5 categories from 2013 to 2023.

Fig. 2 **(a)** Publications and citations trends **(b)** Distribution of categories **(c)** The publication trends of top 5 categories

3.2 Analysis of journals

There are 295 journals publishing a total of 997 articles, which are classified into 85 Web of Science categories. The top 10 journals were listed in Table 1, including Sustainability with 55 articles (5.517%), Frontier in Sustainable Food Systems with 44 articles (4.413%), Agricultural Systems with 38 articles (3.811%) and so on. Agricultural Systems ranks highest in terms of the number of citations, H-Index and Journal Citation Index, despite being third in the number of publications. It means the high productivity and significant academic influence in CSA topics. Agriculture Ecosystems Environment has the highest average citation per paper with the earliest initial year in 2014, suggesting the high academic value of this journal. Additionally, the top 10 journals are closely related to sustainable development in agriculture and the environment, this aligns with the Web of Science category analysis.

3.3 Collaborative network analysis of countries

The top 10 productive nations are listed in Table 2 and include four European, three African, one American, and one Asian nations. The majority of nations started their studies in 2014. The United States of America leads the field with 170 articles (17.03% of 997 articles),

Table 1 The top 10 most productive journals from 2013 to 2023

No.	Publication Titles	Total publication	Percentage (%)	Impact factor	H-Index	Number of citations	Average citation per paper	Initial year	Journal Citation Indicator (JCI)
1	SUSTAINABILITY	55	5.52	3.9	13	494	8.98	2017	0.67
2	FRONTIERS IN SUSTAINABLE FOOD SYSTEMS	44	4.41	4.7	9	288	6.55	2019	0.76
3	AGRICULTURAL SYSTEMS	38	3.81	6.6	21	1148	39.16	2015	2.3
4	HELIYON	29	2.91	4	7	171	5.9	2019	0.8
5	AGRICULTURE BASEL	22	2.21	3.6	7	151	6.86	2019	1.07
6	SCIENCE OF THE TOTAL ENVIRONMENT	21	2.11	9.8	12	318	15.14	2017	1.68
7	AGRICULTURE ECOSYSTEMS ENVIRONMENT	20	2.01	6.6	13	840	42	2014	1.71
8	JOURNAL OF CLEANER PRODUCTION	20	2.01	11.1	12	566	28.3	2016	1.53
9	AGRONOMY BASEL	18	1.81	3.7	7	177	9.83	2020	1.04
10	LAND USE POLICY	18	1.81	7.1	14	576	32	2017	1.46

followed by Kenya (27.33%) with 127 articles, Germany (24.42%) with 124 articles. Since certain publications might be attributed to various countries, the overall percentage is higher than 100%. The quantity of publications reflects the degree of activity that various nations have in a given field. In general, CSA is becoming more and more popular in both developed and developing nations. USA (27.13), Kenya (26.96), and the Netherlands (26.69) are the top three countries with the highest academic impact, as indicated by their average citation counts. In Fig. 3(a), we can see that international cooperation often occurs in multiple countries. Figure 3(b) confirms this international cooperation, and the different colors in VOSviewer clusters represent groups of countries with frequent research collaborations. These patterns are largely influenced by institutional partnerships, geographical and climatic conditions, and regional agricultural challenges, shaping global research networks in CSA. In Fig. 3(c), Netherlands is the earliest country to conduct research on CSA in 2013 among the most productive countries, other productive countries began their research in 2014, such as USA, Kenya, Germany, China, England and Italy.

3.4 Analysis of institutions

The institutions analysis provides more detailed insight into the research landscape, highlighting the important institutions and cooperative networks in the field. Table 3 lists the top ten productive institutions worldwide, including four international affiliations, which suggest significant cross-regional cooperation. This can also be confirmed by the resulting map of Citespace (Fig. 4), CGIAR, International Maize & Wheat Improvement Center (CIMMYT), and International Livestock Research Institute (ILRI) ranked the top three in centrality, the three institutions focus extensively on agriculture, environmental science, science technology, and food security.

3.5 Analysis of authors

An analysis of the authors' publication volumes offers insights into the leading scholars and core research within a specific field. Table 4 provides details on the key authors, including their names, the number of publications, and the average citations per article (derived from VOSviewer analysis and statistics). Figure 5 illustrates the network of authors in the research. Significant differences in research focus are observed among the scholars. Jat, M.L., the most productive author, is affiliated with CIMMYT and has published 16 papers, which have accumulated 416 citations, averaging 26.00 citations per paper. Jat, M.L.'s research spans both natural and social science aspects of CSA. One of his most cited studies explores the effects of CSA practices on improving soil organic carbon (SOC) pools and enzyme activities in rhizosphere and bulk soil, which contribute to enhanced nutrient cycling. Assessing CSA effects should consider the variability in rhizosphere and bulk soil responses, inconsistencies in carbon inputs and SOC accumulation across cropping systems, and the sensitivity of microbial enzyme activity to environmental factors (Jat et al., 2021). Additionally, Jat, M.L.'s collaborative work examines key drivers influencing the CSA adoption, including demographic factors, farm plot, market access, socio-economic conditions, climate risks, and the availability of extension services and training programs. However, adoption challenges persist due to increasing land fragmentation and inefficient

Table 2 The top 10 most productive countries in the world

Rank	Countries/Regions	Total publication	Percentage (%)	Citations	Average Citations
1	USA	170	17.03	4612	27.13
2	KENYA	127	12.73	3424	26.96
3	GERMANY	124	12.42	2088	16.84
4	CHINA	113	11.32	1753	15.51
5	NETHERLANDS	107	10.72	2856	26.69
6	INDIA	106	10.62	2181	20.58
7	ETHIOPIA	95	9.52	1139	11.99
8	ENGLAND	74	7.41	1868	25.24
9	ITALY	63	6.31	2591	41.13
10	SOUTH AFRICA	53	5.31	1359	25.64

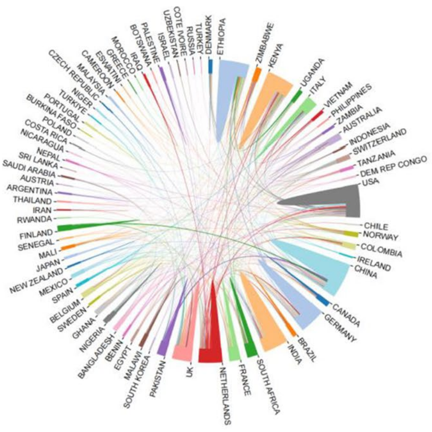
agricultural land rental market, which limit small farmers' ability to adopt CSA practices (Aryal et al., 2018).

3.6 Analysis of the top 10 co-cited papers

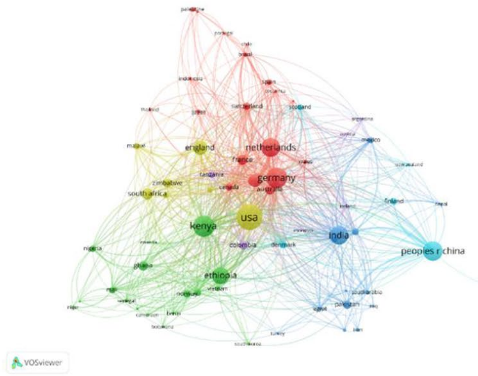
Co-citation analysis measures the frequency by which two documents are cited together. Papers with high co-citation frequencies and centrality construct a knowledge base or fundamental theories for subsequent research. Table 5 highlights the top 10 co-cited papers, each with at least 29 times of co-citation. Figure 6 visualizes the network of these co-cited references, offering insights into their interrelations and significance in the field.

"Climate-smart agriculture for food security", authored by Lipper L et al., was the most co-cited reference (Fig. 6.). Lipper et al. (2014) summarized CSA collaborative efforts among the main stakeholders including local farmers, researchers, extension workers, and private and civil sectors to promote climate-resilient strategies through key initiatives: (1) generating empirical evidence; (2) strengthening local institutions; (3) aligning climate and agricultural policies and (4) merging climate and agricultural financing. This article provided a clear framework and theoretical basis for future macro and micro-level research on the topic of CSA. Theoretically, in the second most co-cited reference, the article "Climate-smart agriculture: what is it good for?" by Taylor (2018), identified four significant challenges inherent in the CSA framework by demonstrating various case-study: (1) the absence of metrics; (2) the resilience paradox; (3) the lack of successful case studies and diversified agriculture; (4) the overlooked role of consumption.

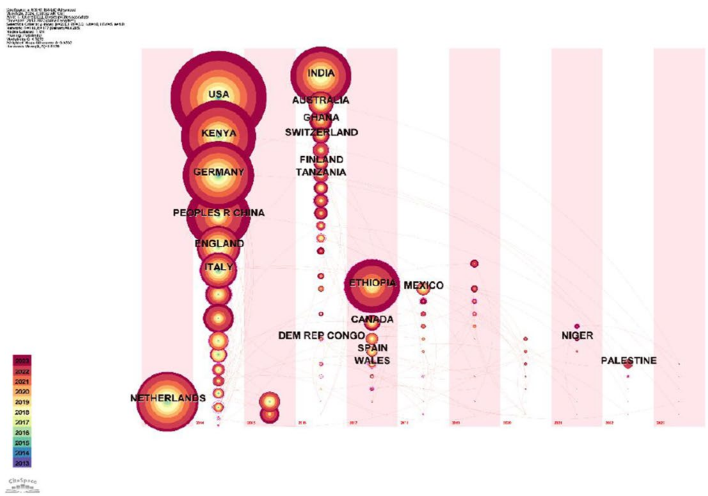
Based on the above two articles, the fifth co-cited article "The climate-smart village approach: framework of an integrative strategy for scaling up adaptation options in agriculture" introduces the climate-smart village (CSV) strategy as a means of performing agricultural research for development to generate sufficient empirical evidence at local scales in Southeast Asia, South Asia, West Africa, East Africa and Latin America. This approach focuses on identifying the most effective CSA options, their optimal locations, underlying reasons, and implementation methods. It emphasizes horizontal scaling out through peer-to-peer knowledge sharing to locally advocate CSA options among all stakeholders. Additionally, it facilitates vertical scaling up by researching the effectiveness of practices, technologies, services, procedures, and institutional alternatives. Using participatory meth-



(a) Network of cooperative relationships among countries



(b) Network of countries involved in the research



(c)Time zone of countries engaged in the research

Fig. 3 (a) Network of cooperative relationships among countries (**b**) Network of countries involved in the research **(c)** Time zone of countries engaged in the research

ods, the CSV strategy seeks to derive insights and lessons for policymakers, agricultural development workers, and investors from local to international scopes (Aggarwal & Jarvis, 2018). It is noted for its potential to effectively scale out promising CSA technologies, practices, and services based on initial study findings.

Practically, in the third, fourth, and sixth most co-cited references, econometric models were used to study the determinants, effects, synergies, and trade-offs of CSA in specific sites. In "Farmers' prioritization of climate-smart agriculture (CSA) technologies" by Khatri-Chhetri A (2017), an ordered Probit model was employed to examine the factors of farmers' adoption of CSA across four distinct rainfall zones in India. The study found that

Table 3 The top 10 productive institutions

Institution	Country/Region	Publications	Percentage (%)	H-index	Citations	Average citations	Centrality	Year
CGIAR	International	153	15.35	36	4,742	31	0.4	2014
Wageningen University & Research	Netherlands	71	7.12	26	2,018	27.64	0.09	2013
Alliance	Africa	55	5.52	25	2956	53.75	0.05	2014
International Center for Tropical Agriculture - CIAT	International	50	5.02	25	2835	56.7	0	2014
CIMMYT	International	45	4.51	21	1288	28.62	0.17	2016
International Livestock Research Institute (ILRI)	International	41	4.11	20	2258	55.07	0.22	2014
Haramaya University	Ethiopia	41	4.11	11	455	11.1	0.04	2019
Indian Council of Agricultural Research (ICAR)	Indian	29	2.91	9	337	11.62	0.02	2016
Chinese Academy of Sciences	China	25	2.51	11	377	15.08	0.12	2014
University of Leeds	England	22	2.21	13	687	28.63	0.16	2015

farmers' choices are significantly impacted by local climatic conditions, socio-economic factors, and their willingness to invest in available technologies. In "Increasing resilience of smallholder farmers to climate change through multiple adoption of proven climate-smart agriculture innovations. Lessons from Southern Africa", multi-nominal logistic regression is utilized to examine the determinants of both single and combined adoption in Malawi and Zimbabwe. Additionally, regression adjustment using inverse probability weighting is utilized to assess how various adoption patterns affect farm productivity and income. Findings indicate that the multiple choices of CSA practices are primarily associated with factors such as the availability of essential resources (total income, credit and information), education, and farm size. Furthermore, those who adopt conservation agriculture, stress-tolerant varieties, concurrently demonstrate significantly higher benefits in both productivity and income compared to those who adopt them separately. The study in Southern Africa examined the impact of conservation agriculture (CA) on adaptation and productivity, revealing positive impacts in the two pillars but no significant effect on mitigation. Seasonal drought is lessened in CA systems, which preserve better infiltration rates and soil moisture. However, substantial increases in yield and profitability often emerge only after two to five crop-

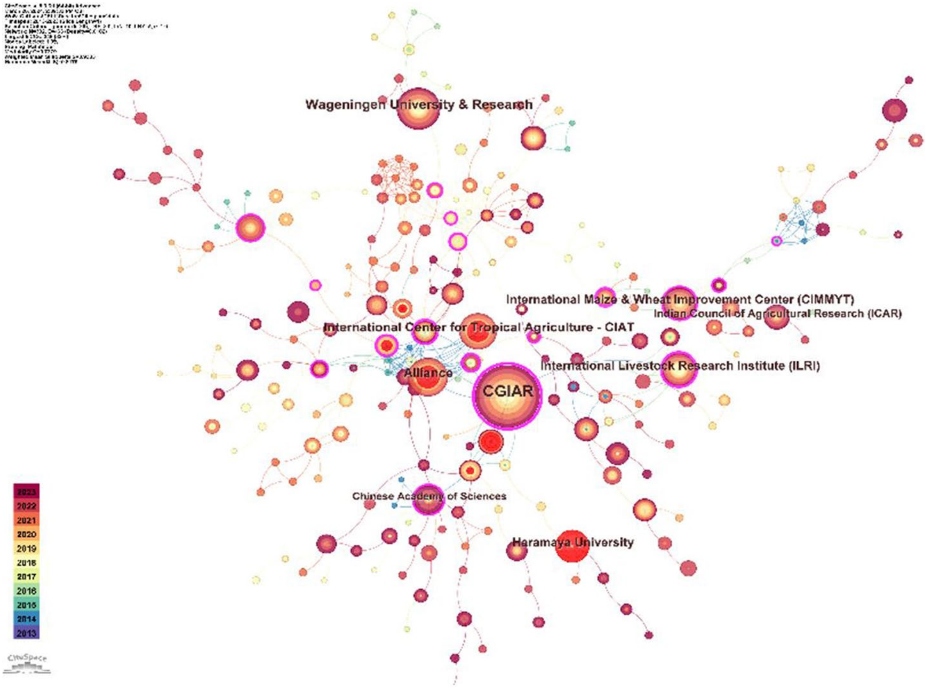


Fig. 4 Network of institutes in the research

Table 4 The list of top 10 most productive authors

Rank	Author	Publications	Citations	Average Citations
1	Jat, M. L.	16	416	26.00
2	Thierfelder, Christian	14	411	29.36
3	Dougill, Andrew J.	12	333	27.75
4	Bedadi, Bobe	10	52	5.20
5	Jat, H. S.	10	214	21.40
6	Solomon, Dawit	10	92	9.20
7	Whitfield, Stephen	10	160	16.00
8	Fritz, Christian	9	222	24.67
9	Tao, Fulu	9	188	20.89
10	Krupnik, Timothy J.	8	207	25.88

ping seasons. In the short term, farmers unable to wait for multiple seasons may find CA more appealing due to its immediate economic benefits and lower labor needs (Makate, Makate, Mango et al., 2019; Thierfelder et al., 2017).

In the ninth and tenth co-cited articles, the specific appraising process was used for the comprehensive analysis, verification and triangulation of CSA, the CSA rapid appraisal combines common participatory rural appraisal and rapid rural appraisal, can collect qualitative and quantitative information from a variety of stakeholders and then carrying out the analysis of resource mapping, climatic chronologies, historical timelines, agricultural

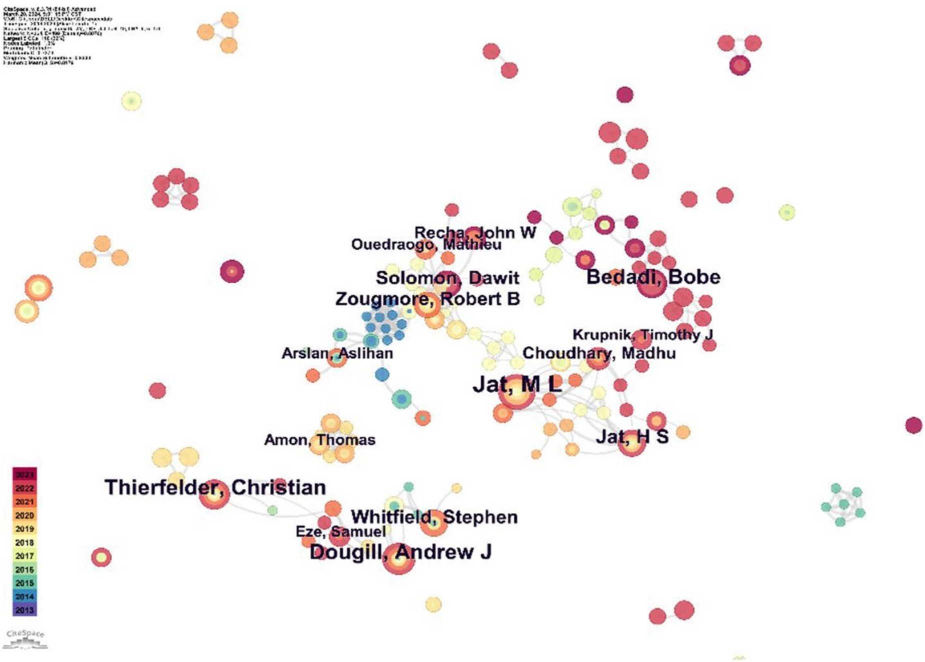


Fig. 5 Network of authors in the research

schedules, organizational schematics, pairwise ranking matrices and so on (Mwongera et al., 2017). In Mali, the Climate-Smart Agriculture Prioritization Framework, leaded by the Agency for Environment and Sustainable Development, involves a systematic approach to identify, assess (through cost-benefit analysis), and prioritize climate-smart alternatives and portfolios (combinations of CSA alternatives). The framework encompasses four key phases: identifying regions of vulnerability and agricultural systems suitable for pertinent CSA practices, selecting optimal CSA practices, conducting cost-benefit analyses, and developing action plans. The process has yielded valuable insights, results, and lessons, providing evidence-based decision supports to pinpoint investment priorities in CSA (Andrieu et al., 2017).

The seventh and eighth articles are about analysis of the history evolution, contexts, and trends that have shaped CSA discourse. CSA owns the characteristics of social, economic, and management dimensions and originated mainly from agriculture, development, and climate change (Chandra et al., 2018; Partey et al., 2018). This can be confirmed from the overlay map (Fig. 7) below by Citespace. The dual-map overlay shows that papers are currently published mostly in the discipline of “Economics, Economic, Political”, “Veterinary, Animal, Science” and “Ecology, Earth, Marine” and are built on the disciplines of “Economics, Economic, Political” and “Plant, Ecology, Zoology” on the right hand of the map.

3.7 Analysis of keywords

Keywords serve as the key elements of particular research, offering insights into research trends and evolution. The frequency of keywords reflects the research objectives and direc-

Table 5 The top 10 co-cited papers and authors

Rank	Freq	Author (Year)	Source	Co-cited reference (DOI)
1	67	Lipper L (2014)	NAT CLIM CHANGE	Climate-smart agriculture for food security (https://doi.org/10.1038/nclimate2437)
2	56	Taylor (2018)	J PEAS-ANT STUD	Climate-smart agriculture: what is it good for? (https://doi.org/10.1080/03066150.2017.1312355)
3	55	Khatri-Chhetri A (2017)	AGR SYST	Farmers' prioritization of climate-smart agriculture (CSA) technologies (https://doi.org/10.1016/j.agsy.2016.10.005)
4	42	Makate C (2019)	J EN-VIRON MANAGE	Increasing resilience of smallholder farmers to climate change through multiple adoption of proven climate-smart agriculture innovations. Lessons from Southern Africa (https://doi.org/10.1016/j.jenvman.2018.10.069)
5	34	Aggarwal PK (2018)	ECOL SOC	The climate-smart village approach: framework of an integrative strategy for scaling up adaptation options in agriculture (https://doi.org/10.5751/ES-09844-230114)
6	34	Thierfelder C (2017)	FOOD SECUR	How climate-smart is conservation agriculture (CA)? - its potential to deliver on adaptation, mitigation and productivity on smallholder farms in southern Africa (https://doi.org/10.1007/s12571-017-0665-3)
7	32	Chandra A (2018)	CLIM POLICY	Climate-smart agriculture: perspectives and framings (https://doi.org/10.1080/14693062.2017.1316968)
8	32	Partey ST (2018)	J CLEAN PROD	Developing climate-smart agriculture to face climate variability in West Africa: Challenges and lessons learnt (https://doi.org/10.1016/j.jclepro.2018.03.199)
9	30	Mwongera C (2017)	AGR SYST	Climate smart agriculture rapid appraisal (CSA-RA): A tool for prioritizing context-specific climate smart agriculture technologies (https://doi.org/10.1016/j.agsy.2016.05.009)
10	29	Andrieu N (2017)	AGR SYST	Prioritizing investments for climate-smart agriculture: Lessons learned from Mali (https://doi.org/10.1016/j.agsy.2017.02.008)

tion. To reduce the bias of keyword analysis, the keywords of "climate smart agriculture", "climate smart agriculture (CSA)", "climate -smart agriculture", and "climate -smart agriculture (CSA)" were merged into "climate-smart agriculture", and "impact" was merged into "impacts". Table 6 presents the 20 most frequently mentioned keywords in publications, the keyword "climate-smart agriculture" was mentioned in 413 publications and began in 2013 belonging to cluster #10, other keywords follow a similar pattern: "climate change" (214), "impacts" (173), "adaptation" (139), "food security" (125). These keywords are visualized in Fig. 8(a). The keywords of "climate change", "food security", "adaptation" and "productivity" reveal researches on pillars of CSA. Many research conducted empirical studies to test the impact of CSA on these three aspects in various countries.

3.8 Analysis of keywords clusters

Keywords cluster analysis is a statistical technique for categorizing based on similarities, with the goal of identifying distribution of reference related to a specific topic. Two metrics, namely Modularity (Q-score) and Silhouette (S-score), are employed to assess the quality of the clustering. A Q-score exceeding 0.3 suggests that the structure of the relationships is significant. An S-score above 0.5 indicates that the clustering is reasonable, while an S-score

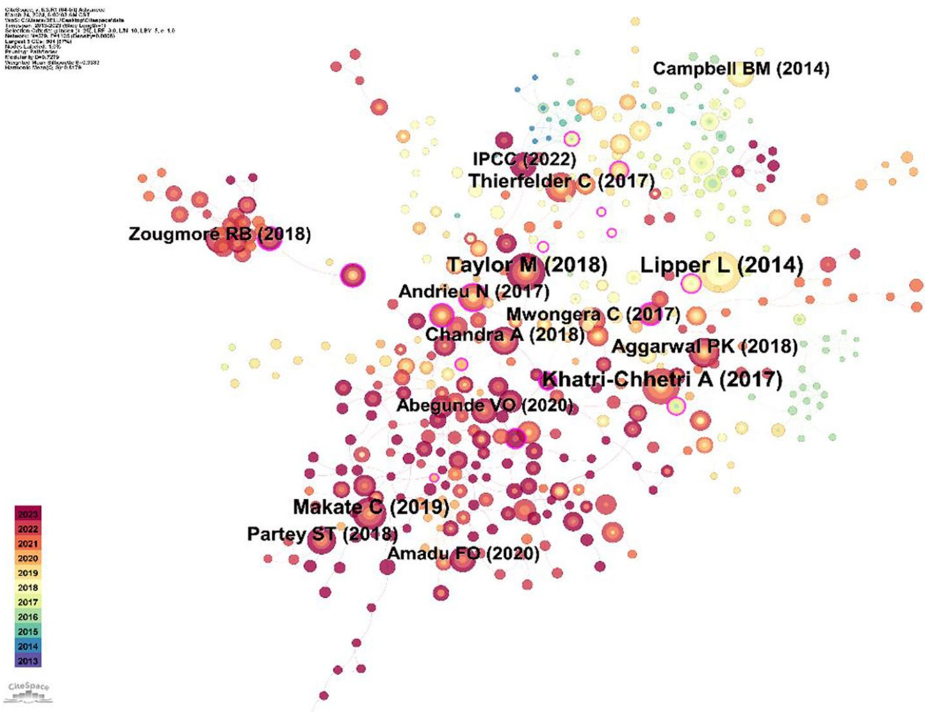


Fig. 6 Network of co-cited references in the research

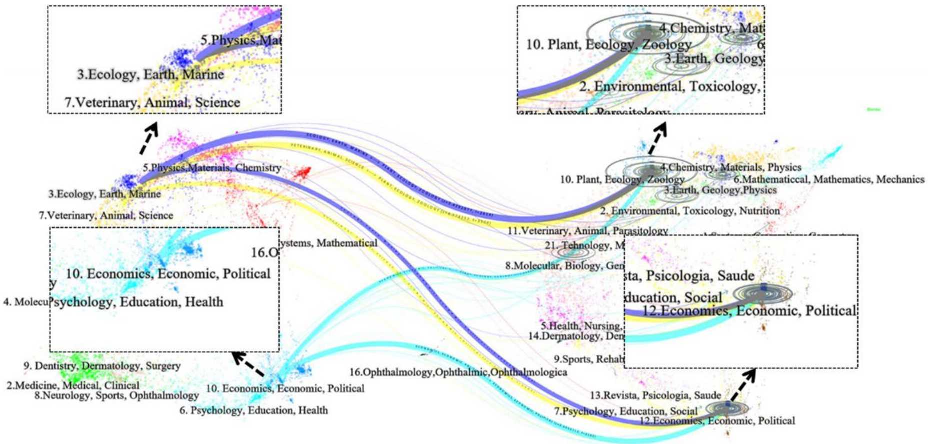


Fig. 7 A dual-map overlay of the science mapping literature

Table 6 Top 20 keywords with the most frequency

No.	Keyword	Count	Year	Cluster ID
1	climate-smart agriculture	413	2013	#10
2	climate change	214	2015	#10
3	impacts	173	2014	#8
4	adaptation	139	2015	#0
5	food security	125	2015	#10
6	management	115	2014	#8
7	conservation agriculture	108	2014	#8
8	systems	103	2015	#10
9	adoption	96	2015	#10
10	smallholder farmers	85	2016	#8
11	productivity	79	2016	#10
12	soil	74	2017	#2
13	agriculture	65	2014	#8
14	farmers	60	2015	#0
15	yield	55	2015	#13
16	variability	51	2016	#5
17	technology	50	2017	#2
18	africa	48	2014	#8
19	sustainable intensification	45	2016	#8
20	tillage	40	2016	#2

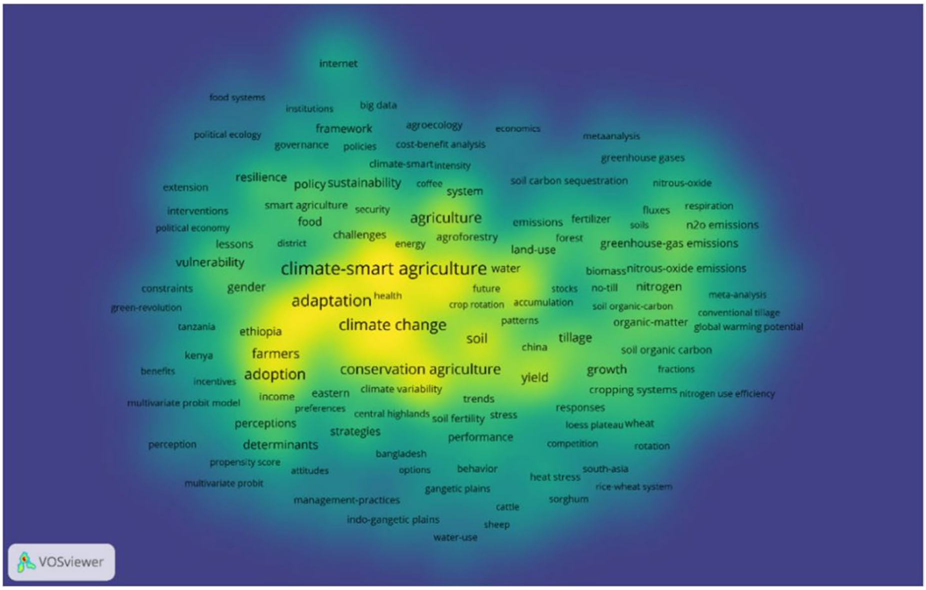
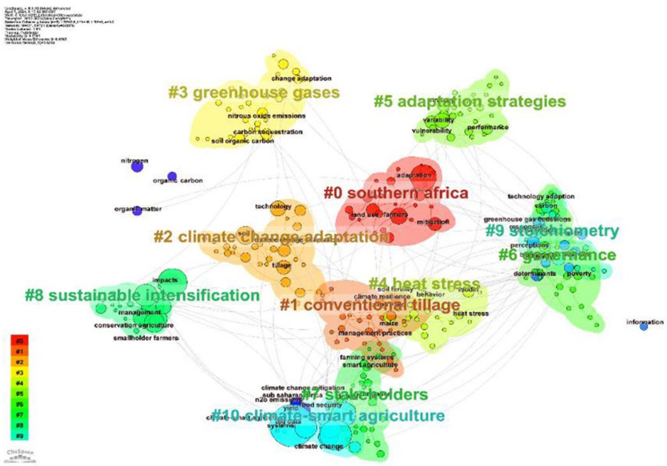
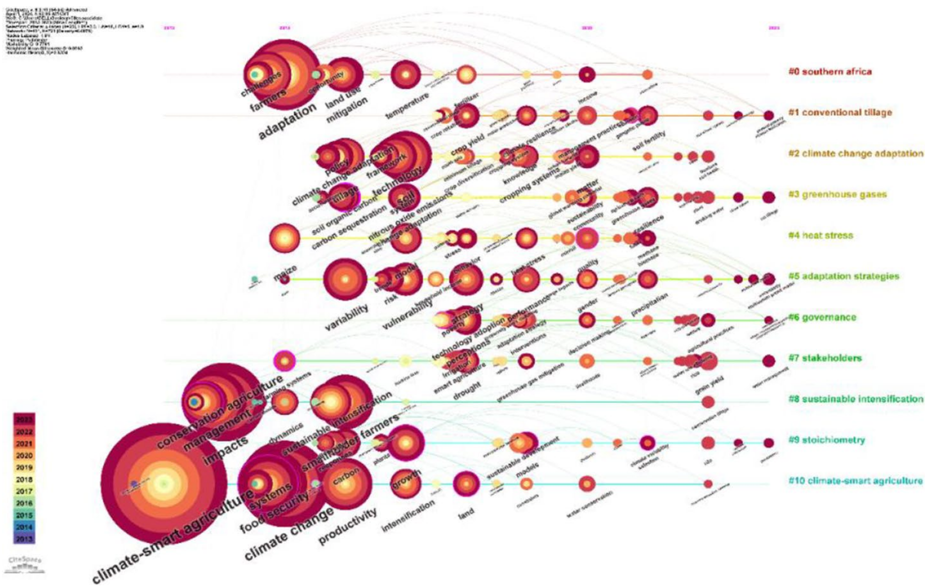


Fig. 8 (**a**) Visualization of keywords co-occurrence

over 0.7 implies that the clustering is both effective and convincing. CiteSpace was utilized to cluster the keywords. As shown in Fig. 9 (Q = 0.7781, S = 0.8903), the top 11 clusters were identified and marked with a "#" in the cluster map. The timeline of the keywords within 11 clusters is visualized in Fig. 9 (b). The following will provide a detailed analysis of the top 5 clusters.



(a) The top 11 clusters in keywords co-occurrence



(b) The timeline of keywords in the top 11 clusters

Fig. 9 (**a**) The top 11 clusters in keywords co-occurrence (**b**) The timeline of keywords in the top 11 clusters

Cluster #0 “southern Africa” highlights the regional application of CSA practices in addressing Southern African vulnerability to climate change (Fig. 10). Especially Zambia, Malawi and Mozambique, encompassing the Chinyanja Triangle have gained much attention in CSA research (Mango et al., 2018). Climate change is a global challenge to agriculture, particularly smallholder farmers in Southern Africa, exacerbating food insecurity and undermining livelihoods (Kangogo et al., 2021; Long et al., 2016). In response, CSA offers an opportunity to adapt to climate change and reduce GHG (Abegunde et al., 2020; Kassa & Abdi, 2022). CSA practices, such as minimum tillage, crop rotation, and mulching, have demonstrated significant benefits in improving soil health and water retention. These practices have been shown to enhance agriculture adaptation during extreme climate events, such as El Niño, when integrated with stress-tolerant crop varieties (Makate et al., 2017; Nyagumbo et al., 2022; Thierfelder et al., 2016). Additionally, land use and land cover changes significantly influence SOC dynamics and carbon sequestration in Southern African agroecosystems. Long-term studies in Zambia also confirm that CSA practices improve water infiltration rate and buffering capacity against water stress, contributing to resilience against climate extremes (Mhlanga & Thierfelder, 2021).

Despite these benefits, significant challenges are in barriers of farmers’ adoption, particularly among smallholder farmers. Limited access to credit, agricultural extension services, combined with wealth-related inequalities constrain adoption rates in Zimbabwe and other parts of Southern Africa (Makate et al., 2019). Gender disparities further exacerbate these challenges, as women farmers often lack the resources and decision-making authority to implement CSA practices effectively (Khoza, 2022; Khoza et al., 2019, 2022). Additionally, gaps in institutional support and policy frameworks hinder the scalability of these practices (Antwi-Agyei et al., 2018; Dougill et al., 2017). The barriers in adoption indicate the limitations of a purely agronomic approach to CSA. Nevertheless, significant opportunities exist to overcome these barriers. Participatory approaches that integrate farmer perspectives and promote cross-sectoral collaboration can strengthen household capacity to address locally experienced constraints in Africa (Clay & Zimmerer, 2020; Jew et al., 2020). Besides that, the spread of agricultural digitalization and technology transfer offers an excellent opportunity to increase agricultural production and improve digital maturity, further supporting the integration of climate-smart innovation and sustainable CSA implementation (Biró et al., 2021). Overall, this cluster helps clarify both the potential and the limitations of CSA in Southern Africa, highlighting the need for future research to integrate adoption-enabling environments with digitalization effectiveness.

Cluster#1 “conventional tillage” contains 93 articles from 2017 to 2023(Fig. 11), mainly about the effects comparison between conventional tillage and CSA tillage practices, such as no tillage, conventional tillage with straw mulch and no tillage with straw mulch (Lazcano et al., 2022; Yuan et al., 2023a). The research in this cluster mostly is in natural science. No-

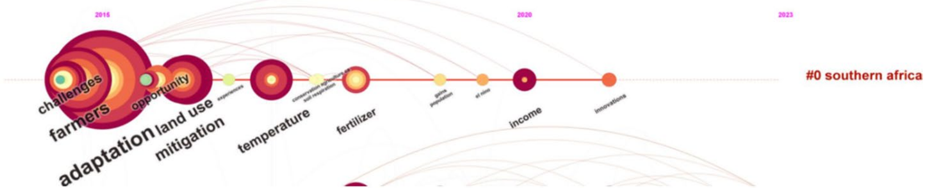


Fig. 10 High-impact members of Cluster #0

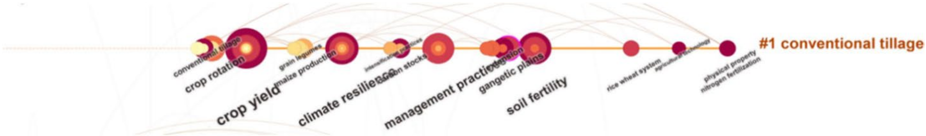


Fig. 11 High-impact members of Cluster #1

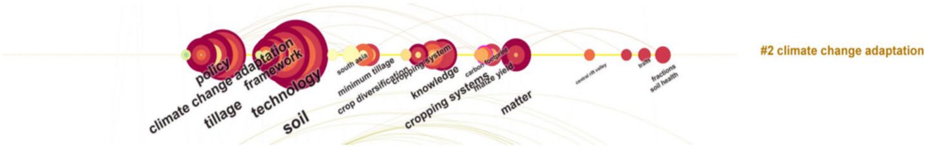


Fig. 12 High-impact members of Cluster #2

tillage can synergistically reduce GHG emissions, enhance soil fertility, and improve energy efficiency and productivity in rice-wheat system (Kakraliya et al., 2022; Yan et al., 2023). Certain research emphasizes that when combined, no-tillage practices and cover crops can sustain crop yield by enhancing soil health in maize production (Huang et al., 2020; Vatsa et al., 2023). Specifically, in Gangetic plains, CSA tillage improved the biomass yield, net farm revenue and economic effectiveness (Kakraliya et al., 2022). What's more, this CSA practice increased soil bulk density, soil ammonia nitrogen, total nitrogen, microbial biomass nitrogen, nitrogen storage, and reduced soil nitrate nitrogen in semi-arid climates (Yuan et al., 2023b). No tillage greatly raised the macro-, meso- and micro-aggregate associated soil carbon, phosphorus and biological pools compared with conventional tillage under the rice-wheat cropping system (Sharma & Singh, 2023).

The impact of no-tillage on yield is controversial (Yan et al., 2023), which poses a challenge for its widespread adoption. Yield stability indexes showed no significant differences in yield stability between no-tillage and conventional tillage although no-tillage exhibited a better stability in variable-weather years in certain cropping systems. Moreover, no-tillage resulted in a significantly lower yields across variable-weather years (Daigh et al., 2018). The co-benefit potential of no-tillage on GHG emissions, soil fertility and crop yields depend upon local conditions, soil attributes, and field management practices (Yan et al., 2023). These inconsistent findings raise questions about the generalizability of CSA tillage and highlight the need for more context-specific and adaptive implementation.

Cluster #2 "climate change adaptation" (CCA) contains 294 articles from 2016 to 2022(Fig. 12), and emphasizes the multifaceted interventions of CSA in enhancing resilience to climate risks through policy frameworks, technology, market-based mechanisms, and on-farm practices. "Climate Smart Land Reform" (CSLR) has been suggested as a policy framework that integrate land reforms with the CSA approach, encompassing components such as redistributing land, changing the tenure system, providing advising services and enhancing markets and infrastructure (Rampa et al., 2020). Technology, including remote sensing and early warning systems, has shown potential in enhancing farmers' resilience capacity to adapt climate risks (Armenta-Medina et al., 2020; Teklu et al., 2023a). Additionally, integrating agriculture into the EU Emissions Trading System (ETS) can permit other controlled industries to purchase balances from the agricultural system under EU climate policies (Verschuuren, 2018). In this context, industrial ecology (IE) offers a systems-based methodological approach to explain the interactions between CCA and socioeconomic system, and the burden or improvement of the interactions on other environmental impacts (Yang et al., 2020). Grounded in this broader systems-oriented perspective, several CSA practices have been widely recognized for strengthening adaptive capacity. Among the most frequently adopted, soil and water conservation, crop diversification, income diversification and adjusting planting times have shown a robust positive impact on household income and food security. These practices not only mitigate farmers' exposure to risks and crop failures but also contribute to enhancing CCA (Shahzad et al., 2021; Tesfaye & Tirivayi, 2020; Zakari et al., 2022).

Multiple challenges hinder the mainstreaming of CCA, including insufficient resources, weak stakeholder and institutional collaboration, and lack of program continuity. Nonetheless, effectively integrating CCA into pro-poor Local Economic Development presents a key opportunity to enhance sustainable local development, ensuring both climate resilience and economic stability for vulnerable communities (Ahenkan et al., 2021). Beyond challenges and opportunities, this cluster reflects an emerging integrative logic that positions CCA as a component of local structural development. It brings together policy reform, technological innovation, market mechanisms, and farm-level practices into a coherent framework. CCA here is framed not as a reactive tool, but as a foundational part of inclusive and long-term development planning.

In cluster #3 "greenhouse gases", there are 155 articles from 2016 to 2023 (Fig. 13). Globally, the agriculture sector represents a significant contributor to GHG emissions (Shakoor et al., 2022). CSA practices can greatly improve soil properties by increasing SOC stocks, and significantly mitigate agricultural GHG emissions by reducing nitrous oxide (N_2O) and methane (CH_4) flux across the US Corn-Belt and India wheat farm (Datta et al., 2022; McNunn et al., 2020). It is the same case in Japan and Indo-genetic plains of South Asia, long-term implementation of no-tillage with crop covering systems in organic soybean fields maintains stable crop productivity while reducing global warming potential (Gong et al., 2021). GHG emissions and energy consumption were reduced by over 50% in CSA practices than in traditional practices (Bijarniya et al., 2020).

Challenges exist due to contradictory findings on GHG mitigation in CSA practices. No-tillage is related with higher N_2O emissions while providing only marginal yield increase, raising concerns about its universal applicability. Manure application enhances crop yields but significantly increases carbon dioxide (CO_2) and N_2O emissions. In contrast, biochar application presents a strong coupling effect, reducing CH_4, N_2O, and CO_2 emissions, and increasing crop yield. Notably, its effectiveness is influenced by soil traits: biochar performs better in coarse-textured soils, while no-tillage contributes to N_2O mitigation in fine-textured soils (Shakoor et al., 2022). This suggest that the performance of CSA practices is highly context-dependent, highlighting the need for site-specific optimization practices. These findings also reflect a growing emphasis on GHG emission mechanism-oriented

Fig. 13 High-impact members of Cluster #3

research that moves beyond simplified effect evaluations. Rather than treating mitigation as universally consistent, the literature increasingly explores how interacting factors influence GHG responses.

In cluster #4 "heat stress", there are 130 articles from 2015 to 2021 (Fig. 14). As climate change worsens, extreme heat waves become more frequent, the keyword "heat stress" first appeared in 2019 and keeps a hot theme to the present, particularly in relation to maize, which is highly vulnerable to rising temperatures (Konate et al., 2023; Lizaso et al., 2018). Heat stress affects maize through both climatic and physiological pathways. It alters rainfall patterns, accelerates phenological development, and shortens the grain-filling period, increasing yield variability and the risk of crop failure. High temperatures also impair pollen viability and fertilization, reducing biomass accumulation and grain quality (Luppichini et al., 2023; Moore et al., 2021). Beyond biophysical effects, farmer behavior emerges as a critical social dimension of climate response. Farmers with loss-aversion and probability distortion are more likely to perceive climate threats and adopt CSA practices accordingly, indicating that behavioral response is shaped by cognitive framing rather than purely objective climate risk exposure (Villacis et al., 2021). This highlights the relevance of behavioral economics in understanding CSA adoption dynamics. Methodologically, both econometric models and regional climate simulations were used to estimate the impacts of temperature and rainfall variation on crop production. However, challenges persist in the sensitivity of model outputs to assumptions and parameterization, particularly in crop-climate coupling (Gashure et al., 2022; Kassaye et al., 2021; Laux et al., 2021).

Notably, studies from Ethiopia illustrate the divergent impacts of maximum and minimum temperature increases, showing the challenge of designing CSA strategies that harness beneficial heat exposure while mitigating thermal stress (Kassaye et al., 2021; Zizinga et al., 2022). Beyond agronomic and behavioral responses, gene-level interventions such as overexpression of Arabidopsis Cel1 offer additional opportunities to enhance heat resilience by increasing biomass and enhancing yield in monocot species (Venkata et al., 2020). Overall, this cluster reflects the dual challenge of addressing physiological constraints and behavioral adaptation, and it provides a promising foundation for interdisciplinary CSA frameworks that integrate biophysical modeling, behavioral insights, and genetic innovation.

3.9 Analysis of keywords citation burst

The keywords exhibiting the strongest citation burst at a certain period can effectively indicate the current research hotspots and frontiers. Through the analysis by CiteSpace, the top 18 keywords with the most significant citation bursts have been identified in Fig. 15.

In initial stage, the research focus is characterized by keywords such as "systems", "southern Africa",

"dynamics", "policy", "burkina faso", and "time". The burst strength for these keywords is from 2.21 to 6.1. These terms point to an early focus on agri-food system, policy inte-

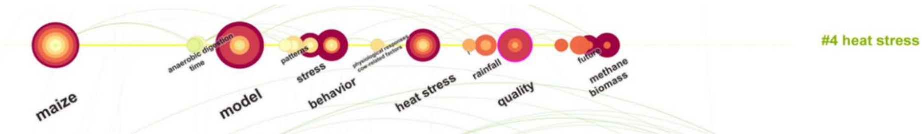


Fig. 14 High-impact members of Cluster #4

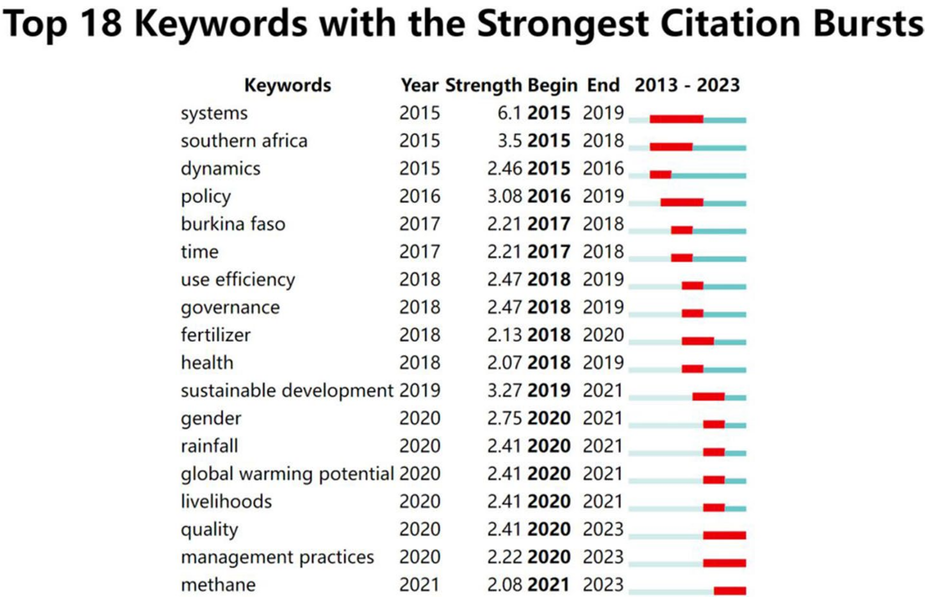


Fig. 15 The top 18 keywords with citation burst (by the commencement year of the burst)

gration, and multiscale agricultural dynamics over time, particularly in climate-vulnerable regions such as Southern Africa and Burkina Faso. One research area centered on policy integration, which laid a critical foundation for subsequent research. A key policy challenge in operationalizing CSA was the identification, valuation, and prioritization of climate-smart options and investment portfolios (Andrieu et al., 2017b; Schaafsma et al., 2018). At the same time, scaling up CSA through policy faced several barriers, including uncertainty in cost-benefit assessments, fragmented knowledge systems, and challenges in ensuring equity concerns (Westermann et al., 2018). A second theme during this period involves in temporal agricultural dynamics, such as whole farm dynamics, soil organic matter dynamics, and the dynamics of the internal soil strength parameters and pore function, which provided critical insights for later research, particularly in cost-benefit analysis and long-term CSA sustainability assessments (Ajayi & Horn, 2016; Descheemaeker et al., 2016; Saiz et al., 2016).

In later stage, research focus on “use efficiency”, “governance”, “fertilizer”, “health”, “sustainable development”, “gender”, “rainfall”, “global warming potential” and “livelihoods”. The burst strength for these keywords is from 2.07 to 3.27. Research on resource use efficiency highlighted that CSA practices in rice-wheat systems significantly improved irrigation water efficiency (by 39.3%) and energy use efficiency (by 43%) (Bijarniya et al., 2020). Additionally, combining nitrogen fertilizer with high organic carbon soil amendments can effectively reduce N_2O emissions and improve nitrogen use efficiency(Wei et al., 2020), contributing to sustainable development. As to soil health, intercropping will promote higher organic matter and nitrogen while lower bulk density (Nyirenda, 2019). However, gender disparities remained a critical challenge, as women farmers faced restricted access to agricultural inputs and extension services (Tsige et al., 2020). The failure to incorporate women into CSA design exacerbated social inequalities and missed key opportunities for inclusive development (Duffy et al., 2021). With regard to climate mitigation, SOC sequestration rates in CSA practices significantly increased, and the global warming potential from CH_4 and N_2O emissions was fully offset by net CO_2 retention under no tillage (Gong et al., 2021). Meanwhile, CSA research moved beyond a sole focus on yield, shifting attention to farmers' livelihoods, which in turn supported farmers in enhancing food security, asset accumulation, and access to services (Sardar et al., 2021).

In the latest stage, the keywords with strong citation burst include "quality", "management practices", and "methane". The latest research transfers to more specific aspect. Soil quality and land management practices have drawn increasing attention, as carbon sequestration potential is highly dependent on local biophysical conditions and the specific management practices in place (Bell et al., 2023). A comprehensive approach, integrating socio-economic, and biophysical factors presents an opportunity to enhance soil quality, restore fertility, and optimize intervention strategies across different farms (Muriithi et al., 2023). In parallel, methane emissions pose a significant challenge as it causes greater long-term damage to yields than any other GHG or climatic variables (Anyaegbu et al., 2023). Paddy fields contribute the highest CO_2-equivalent emissions among crops, with around 60% of these emissions attributed solely to methane due to prolonged water submergence (Ranguwal et al., 2023). To address this challenge, experiments in India have demonstrated that methane emissions from lowland rice fields can be reduced by 40–50% through alternate wetting and drying, planting shorter-duration rice varieties, and applying neem-coated urea based on soil health cards and leaf color charts. Furthermore, dry direct-seeding of rice, which eliminates continuous soil submergence, has shown the potential to reduce methane emissions by 70–75% (Pathak, 2023).

3.10 Limitations

Utilizing CiteSpace and VOSviewer for analysis enables a more structured, accurate and comprehensive examination of literature compared to traditional qualitative reviews. However, certain limitations exist in this study. First, the search was restricted to the WOS Core Collection database, which, while covering a wide range of high-quality literature, may exclude relevant studies in other databases, potentially introducing bias. Second, the inclusion criteria excluded review articles, which may have led to the omission of other type sources. Despite these limitations, the credibility of the WOS Core Collection and the substantial number of publications analyzed ensure that this study effectively captures the structure, key trends, challenges, and possible opportunities in CSA research. Future research should strive to address these limitations for a more comprehensive analysis.

4 Conclusions

This study employed bibliometric methods, using CiteSpace and VOSviewer for visualization and analysis. It systematically summarizes the knowledge development, structure, research frontiers, and identify challenges and possible opportunities among natural and social science over the past decade. The study resulted in several key conclusions: (1) Studies on CSA from 2013 to 2023 can be separated into two stages, a rapidly growing stage began from 2018. Environmental Sciences possesses the highest rank regarding to categorization, followed by Environmental Studies, Agronomy. The journal with the most published articles is Sustainability, followed by Frontier Sustainable Food Systems. (2) Most productive countries began their research in 2014. The United States is the most productive nation, followed by Kenya, Germany. CGIAR is the leading institute in the field. Overall, CSA gains attention both in developed countries and developing countries. Cooperation often occurs in multiple countries and there is no strong link strength among fixed countries. (3) Challenges and opportunities are across horizontal thematic clusters and vertical temporal stages: (1) From horizontal keywords clusters. CSA adoption in Southern Africa cluster is hindered by financial, social, and institutional barriers, while participatory approaches and agricultural digitalization offer opportunities. No-tillage cluster faces inconsistent yield impacts. Climate adaptation struggles with resource, governance, and continuity challenges while pro-poor economic integration offers opportunities. Greenhouse gas cluster presents contradictory findings with opportunities through studying in mechanisms driving GHG fluxes, and heat stress cluster has the dual challenge of addressing physiological constraints and behavioral adaptation, while identifying gene-level interventions as a promising opportunity to enhance heat resilience. (2) From vertically temporal keywords citation bursts. Early research focus on policy integration and agricultural system dynamics with challenges in cost-benefit uncertainties and policy scalability, while later on, incorporating women into CSA design provides key opportunities for inclusive development. In the latest stage, methane emissions from paddy fields have become a major issue. The findings provide a structured foundation for advancing CSA and supporting its scalable and sustainable implementation.

Funding Open access funding provided by The Ministry of Higher Education Malaysia and Universiti Putra Malaysia. This research received no specific funding.

Data availability The datasets generated during the current study are available in the Mendeley Data, https://data.mendeley.com/preview/gkxw34jzdf?a=d1036f35-2613-4af8-b355-3de7eb39430c.

Declarations

Ethics approval and consent to participate Not applicable. This manuscript is a review article and does not involve any studies with human participants or animals performed by any of the authors.

Consent for publication Not applicable.

Competing interests The authors declare that they have no competing interests.

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