Bibliometric Mapping of Climate-Smart Agriculture Research

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Article Info

ABSTRACT

Climate-Smart Agriculture (CSA) has emerged as a strategic framework for addressing the intertwined challenges of climate change, food security, and sustainable agricultural development. This study aims to map the global research landscape of Climate-Smart Agriculture using a bibliometric approach. Data were retrieved from the Scopus database and analyzed using VOSviewer to examine publication trends, co-authorship networks, institutional collaboration, country partnerships, keyword co-occurrence, overlay visualization, and density mapping. The results indicate that CSA research is strongly anchored in the broader discourse of climate change, with dominant themes including food security, adaptation, mitigation, sustainability, and smallholder resilience. The keyword clustering reveals three major intellectual streams: socio-economic resilience, environmental sustainability, and technological innovation. Overlay analysis shows a temporal shift from early vulnerability and adaptation-focused studies toward more recent research emphasizing smart agriculture, precision farming, and digital climate solutions. Collaboration networks demonstrate strong North–South and South–South partnerships, with India, the United States, Kenya, and Ethiopia emerging as key contributors. Institutional mapping highlights the central role of international agricultural research centers and universities in shaping the field. CSA research reflects a mature and interdisciplinary domain that increasingly integrates technological innovation with sustainability objectives. Future research should prioritize inclusive digital solutions, policy implementation analysis, and stronger collaboration among climate-vulnerable regions to enhance the transformative impact of CSA practices.
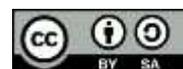
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1. INTRODUCTION

Climate change has emerged as one of the most pressing global challenges of the twenty-first century, exerting profound impacts on agricultural systems worldwide. Rising temperatures, shifting precipitation patterns, increased frequency of extreme weather events, and the proliferation of pests and diseases threaten agricultural productivity, food security, and rural livelihoods [1], [2]. Agriculture is uniquely vulnerable to climate change because it is directly dependent on climatic conditions, yet it is also a significant contributor to greenhouse gas emissions through land-use change, livestock production, and fertilizer application. This dual role—as both victim

and contributor—positions agriculture at the center of global climate mitigation and adaptation efforts. Consequently, there has been an increasing demand for transformative approaches that enhance productivity while simultaneously improving resilience and reducing emissions [3], [4].

In response to these challenges, the concept of Climate-Smart Agriculture (CSA) was introduced as an integrated framework to address the interconnected goals of food security, climate adaptation, and mitigation [5]. CSA is built upon three core pillars: sustainably increasing agricultural productivity and incomes; adapting and building resilience to climate change; and reducing or removing greenhouse gas emissions where possible. Rather than prescribing a single set of practices, CSA encompasses a broad portfolio of context-specific technologies and management strategies, including conservation agriculture, agroforestry, improved crop varieties, efficient irrigation systems, and climate-informed advisory services [5], [6]. This flexible and integrative nature has made CSA a central theme in international agricultural development discourse and policy planning.

Over the past decade, research on CSA has expanded rapidly across disciplines such as agronomy, environmental science, economics, social sciences, and policy studies. Scholars have investigated diverse topics including carbon sequestration potential, resilience measurement, adoption barriers among smallholder farmers, gender dimensions of climate adaptation, and the role of digital technologies in climate information dissemination [7], [8]. The interdisciplinary character of CSA research reflects the complexity of agricultural systems and the multifaceted impacts of climate change. As a result, the body of literature has grown not only in quantity but also in thematic diversity, geographic coverage, and methodological approaches.

The rapid expansion of CSA scholarship has been accompanied by increased collaboration among international organizations, research institutions, and policymakers. Global initiatives such as the Global Alliance for Climate-Smart Agriculture and various national adaptation programs have stimulated knowledge production and dissemination. Scientific publications now span multiple regions, with significant contributions emerging from Sub-Saharan Africa, South Asia, and Latin America, where vulnerability to climate change is particularly acute [7]. Furthermore, advancements in remote sensing, modeling tools, and big data analytics have enhanced the analytical capacity of researchers to assess climate risks and evaluate CSA interventions. This evolution underscores the dynamic and networked nature of CSA research landscapes.

Given this accelerating growth, understanding the structure, trends, and knowledge networks within CSA research has become increasingly important. Bibliometric analysis offers a systematic and quantitative approach to mapping scientific literature, identifying influential authors, institutions, countries, journals, and thematic clusters [9]. Through techniques such as co-citation analysis, co-authorship mapping, and keyword co-occurrence analysis, bibliometric studies can reveal intellectual structures, research fronts, and emerging topics within a field. In rapidly evolving domains like CSA, bibliometric mapping provides valuable insights into how knowledge is produced, disseminated, and interconnected across disciplines and regions. Such analyses can inform strategic research planning, highlight knowledge gaps, and guide future interdisciplinary collaborations.

Despite the substantial growth of Climate-Smart Agriculture research, the existing literature remains fragmented across disciplines, regions, and thematic priorities. While numerous empirical and conceptual studies have addressed specific aspects of CSA, there is limited comprehensive synthesis that systematically maps the intellectual structure, collaboration networks, and evolving research themes of the field as a whole. The absence of an integrated bibliometric assessment makes it difficult to identify dominant research clusters, emerging trends, underexplored topics, and disparities

in global research participation. Moreover, without a clear visualization of scholarly networks and thematic evolution, policymakers, funding agencies, and researchers may face challenges in setting strategic priorities and fostering effective collaboration. Therefore, a structured bibliometric mapping of CSA research is necessary to consolidate existing knowledge and provide a clearer understanding of the field's development trajectory. The objective of this study is to conduct a comprehensive bibliometric mapping of Climate-Smart Agriculture research in order to analyze its intellectual structure, publication trends, collaborative networks, and thematic evolution.

2. METHOD

This study employed a quantitative bibliometric research design to systematically map the intellectual structure and development trends of Climate-Smart Agriculture (CSA) research. Bibliometric analysis was selected because it enables the objective evaluation of large volumes of scientific literature through statistical and network-based techniques. The analysis focused on peer-reviewed publications indexed in a comprehensive international scientific database to ensure high-quality and standardized bibliographic information. A structured search strategy was developed using relevant keywords such as "climate-smart agriculture," "climate smart agriculture," and related terms appearing in titles, abstracts, and author keywords. The search was limited to articles and reviews published in English to maintain consistency in analysis. The time span covered publications from the earliest available year in the database until the most recent complete year at the time of data collection. All retrieved records were exported in compatible formats containing full bibliographic information, including authors, affiliations, abstracts, keywords, references, and citation data.

Data cleaning and preprocessing were conducted prior to analysis to ensure accuracy and consistency. Duplicate records were removed, and variations in author names, institutional affiliations, and keywords were standardized to avoid fragmentation in network visualization. Bibliometric indicators such as annual publication growth, total citations, average citations per document, and h-index values were calculated to assess research performance and impact. Descriptive statistical analysis was used to examine publication trends over time, leading journals, productive authors, influential institutions, and contributing countries. These indicators provided an overview of the productivity and influence of different actors within the CSA research landscape.

To explore the intellectual and collaborative structure of the field, network analysis techniques were applied using bibliometric mapping software. Co-authorship analysis was conducted to examine collaboration patterns among authors, institutions, and countries. Co-citation analysis was used to identify influential references and uncover the foundational knowledge base of CSA research. Additionally, keyword co-occurrence analysis was performed to detect major research themes, thematic clusters, and emerging topics within the literature. Network visualization maps were generated to illustrate relationships among nodes, where node size represented frequency or impact, and link strength indicated the intensity of relationships.

3. RESULT AND DISCUSSION
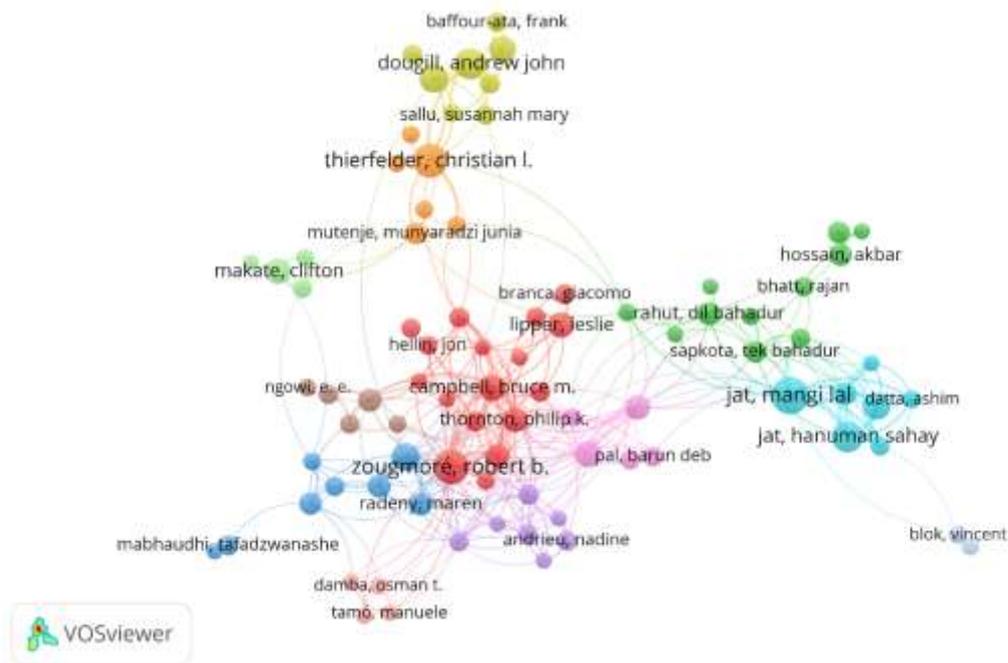**Co-Authorship Analysis**

Figure 1. Author Visualization
Source: Data Analysis

Figure 1 illustrates a well-structured and interconnected research landscape within Climate-Smart Agriculture (CSA). The largest and most central node appears to be Zougmoré, Robert B., indicating his strong influence and extensive collaboration within the field. He is closely connected with authors such as Campbell, Bruce M., Thornton, Philip K., and Radeny, Maren, forming a dominant cluster that reflects a core research group focusing on climate adaptation and agricultural resilience in developing regions. The presence of multiple colored clusters suggests thematic and institutional collaboration groupings, with each cluster representing a distinct but interconnected research community. Another prominent cluster includes authors such as Jat, Mangi Lal, Bhat, Rajan, and Rahut, Dil Bahadur, which likely reflects research concentrated on agronomic innovations, conservation agriculture, and productivity enhancement under climate stress conditions. Meanwhile, authors like Douxchamps, Sabine and Thierfelder, Christian L. form another visible collaborative group, potentially focusing on sustainable intensification and farming systems in Sub-Saharan Africa. The relatively dense linkages between clusters indicate cross-regional and interdisciplinary collaboration, suggesting that CSA research is not isolated within single institutions or countries but is shaped by global knowledge exchange networks.
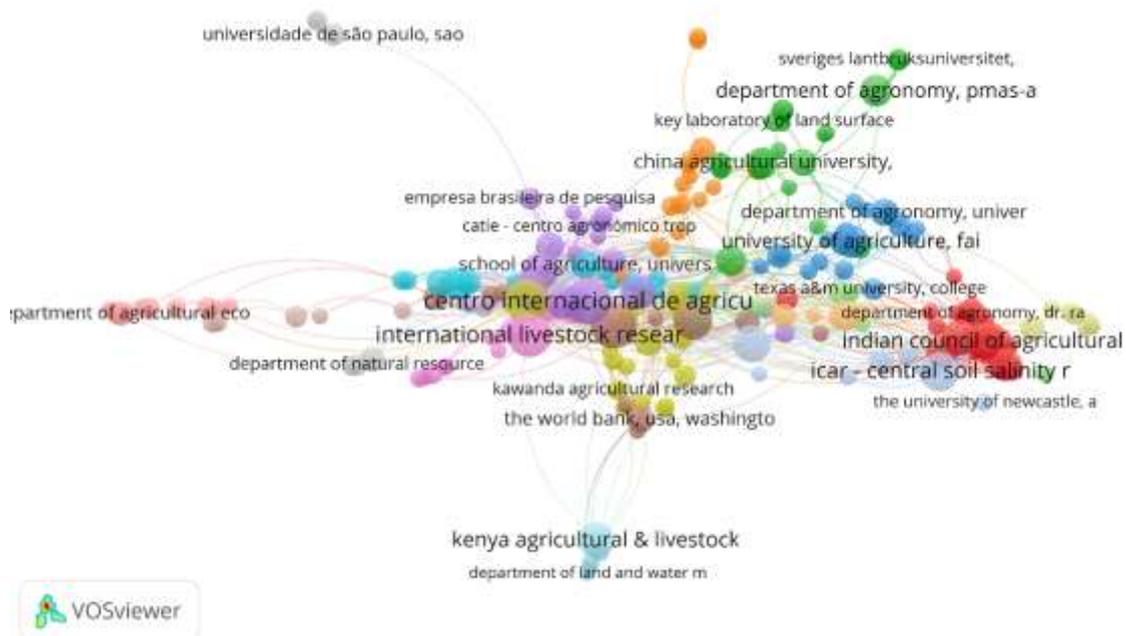
Figure 2. Institution Visualization
Source: Data Analysis

Figure 2 reveals a highly interconnected and globally distributed research structure in Climate-Smart Agriculture (CSA). The most prominent and central node appears to be Centro Internacional de Agricultura Tropical (CIAT), indicating its pivotal role as a global hub in CSA research collaboration. CIAT is closely linked with institutions such as the International Livestock Research Institute (ILRI), China Agricultural University, the University of Agriculture Faisalabad, and ICAR – Central Soil Salinity Research Institute, reflecting strong cross-continental partnerships spanning Latin America, Africa, and Asia. This suggests that CSA research is heavily driven by international agricultural research centers and national agricultural universities working collaboratively on climate resilience and food security. Distinct clusters represent regional research strengths, such as Indian agricultural institutions (e.g., Indian Council of Agricultural Research), Chinese research bodies (e.g., China Agricultural University and the Key Laboratory of Land Surface), and European institutions (e.g., Sveriges lantbruksuniversitet). African institutions, including Kenya Agricultural & Livestock Research Organization, are also visibly integrated into the network, emphasizing the importance of Sub-Saharan Africa in CSA studies. The presence of global development actors such as The World Bank further indicates policy-driven and funding-linked research collaborations.
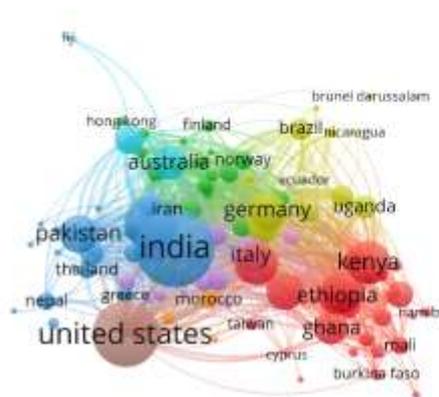
Figure 3. Country Visualization
Source: Data Analysis

Figure 3 highlights a strongly interconnected global research landscape in Climate-Smart Agriculture (CSA), with India, the United States, Kenya, and Ethiopia emerging as the most prominent contributors. India appears as the largest and most central node, indicating its significant publication output and extensive international collaboration. The United States also plays a major bridging role, connecting multiple regional clusters across Asia, Africa, and Europe. Meanwhile, Kenya and Ethiopia form a dense African cluster, reflecting the strong research focus on climate resilience and smallholder farming systems in Sub-Saharan Africa, where climate vulnerability is particularly high. European countries such as Germany, Italy, Norway, and Finland are actively integrated into the network, often collaborating with developing countries. Pakistan and Australia also appear as important regional actors, linking Asian and global research efforts. The dense interlinkages among these countries suggest that CSA research is highly collaborative and transnational, driven by shared concerns about food security, adaptation, and sustainable agricultural transformation.

Citation Analysis

Table 1. Top Cited Literature

Citations	Authors and Year	Title
1,790	[10]	Climate-smart soils
1,568	[4]	Climate-smart agriculture for food security
1,447	[11]	Impact of climate change on crops adaptation and strategies to tackle its outcome: A review
1,124	[12]	Impact of climate change on agriculture and its mitigation strategies: A review
916	[13]	Soil structure and microbiome functions in agroecosystems
704	[14]	Digitalization to achieve sustainable development goals: Steps towards a Smart Green Planet
591	[15]	Soil salinity under climate change: Challenges for sustainable agriculture and food security
468	[16]	Sustainable intensification: What is its role in climate smart agriculture?

| 427 | [17] | Barriers to the adoption and diffusion of technological innovations for climate-smart agriculture in Europe |
| 371 | [18] | Beyond conservation agriculture |

Source: Scopus Database

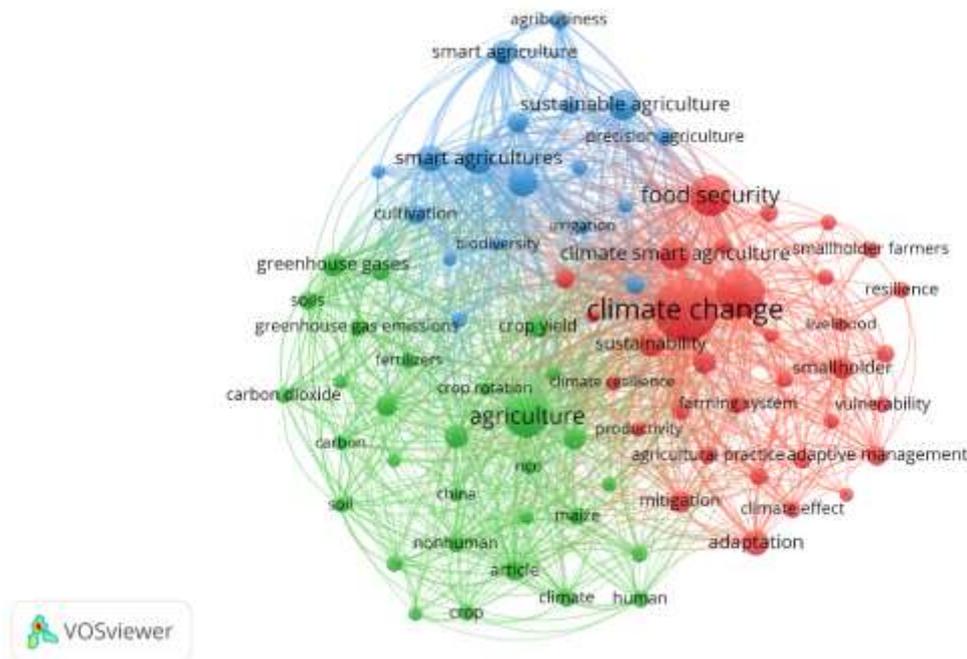**Keyword Co-occurrence Analysis**

Figure 4. Network Visualization
Source: Data Analysis

Figure 4 reveals the intellectual structure of Climate-Smart Agriculture (CSA) research, with climate change emerging as the most dominant and central theme. Its large node size and dense linkages with other keywords indicate that CSA studies are strongly anchored in broader climate discourse. Closely connected terms such as food security, adaptation, mitigation, sustainability, and resilience suggest that the field is fundamentally oriented toward addressing the dual challenge of maintaining agricultural productivity while responding to climate variability and long-term environmental risks. The red cluster appears to represent the socio-economic and resilience-oriented dimension of CSA. Keywords such as smallholder, livelihood, vulnerability, adaptive management, and farming system highlight the strong focus on smallholder farmers, particularly in developing countries. This cluster reflects research examining how agricultural communities adapt to climate stress, manage risks, and sustain food production systems under uncertain climatic conditions. The strong presence of food security within this cluster further reinforces the development-oriented nature of CSA research.

The green cluster is largely associated with environmental and biophysical processes. Terms such as greenhouse gas emissions, carbon dioxide, soil, crop rotation, fertilizers, and biodiversity indicate that a substantial body of research concentrates on mitigation strategies and ecological sustainability. This cluster emphasizes carbon sequestration, soil health, emission reduction, and sustainable land management practices. The prominence of crop-specific terms like rice and maize suggests that staple crops remain central to CSA studies, particularly in regions vulnerable to climate change. The blue cluster highlights the technological and

innovation-driven dimension of CSA research. Keywords such as smart agriculture, precision agriculture, sustainable agriculture, irrigation, and agribusiness demonstrate the integration of digital technologies and modern farming systems into climate adaptation strategies. This suggests a growing convergence between CSA and digital transformation in agriculture, where data-driven approaches, smart irrigation, and precision inputs are increasingly considered key tools for enhancing climate resilience and productivity.

Figure 5. Overlay Visualization
Source: Data Analysis

Figure 5 illustrates the temporal evolution of Climate-Smart Agriculture (CSA) research, with color gradients indicating publication recency. Earlier themes, shown in darker blue tones, are strongly associated with foundational concepts such as adaptation, vulnerability, smallholder, livelihood, and climate effect. This suggests that initial CSA research focused heavily on understanding climate risks, socio-economic vulnerability, and resilience strategies among smallholder farmers, particularly in developing regions. These studies laid the groundwork by emphasizing adaptation mechanisms and the socio-environmental impacts of climate change on agricultural systems. As the field evolved, mid-phase research (green tones) increasingly integrated broader sustainability dimensions, including climate-smart agriculture, food security, sustainability, productivity, and farming systems. This transition reflects a shift from purely vulnerability-based analyses toward more integrated frameworks that combine adaptation, mitigation, and productivity enhancement. During this stage, CSA became more structured conceptually, linking environmental management with agricultural intensification and policy-oriented approaches to ensure long-term food system resilience.

More recent research themes, highlighted in yellow tones, show growing attention to technological and innovation-driven topics such as smart agriculture, precision agriculture, agribusiness, crop systems, and advanced sustainability practices. This indicates that current CSA scholarship is increasingly converging with digital agriculture and smart farming technologies. The temporal pattern suggests a clear trajectory: from vulnerability and adaptation studies, to integrated

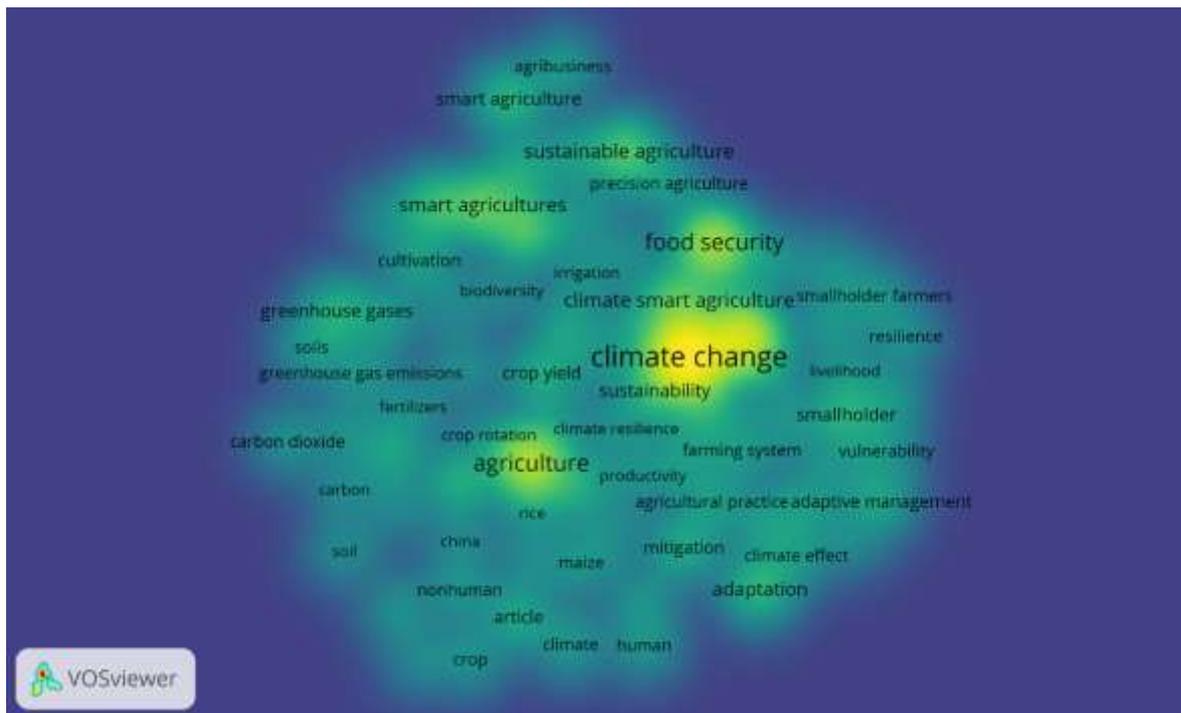sustainability frameworks, and finally toward technology-enabled climate solutions.

Figure 6. Density Visualization
Source: Data Analysis

Figure 6 highlights the most intensively researched themes within Climate-Smart Agriculture (CSA). The brightest and most concentrated area is centered around climate change, indicating that it is the core driving concept in the field. Closely surrounding it are high-density keywords such as food security, climate smart agriculture, sustainability, and agriculture, suggesting that the literature strongly integrates climate adaptation and mitigation efforts with agricultural productivity and long-term sustainability goals. The prominence of these interconnected terms confirms that CSA research is fundamentally structured around balancing environmental resilience with food system stability.

Moderate-density areas extend toward topics such as smallholder, adaptation, mitigation, greenhouse gas emissions, soil, and smart agriculture. This pattern indicates that while socio-economic resilience and emission reduction remain central pillars, there is also growing emphasis on technological innovation and sustainable farming practices. The diffusion of density across environmental, social, and technological keywords demonstrates that CSA is a multidimensional research domain, where climate risk management, ecosystem sustainability, and innovation-driven agricultural transformation are tightly interlinked within the global research agenda.

Discussion

The findings of this bibliometric mapping reveal that Climate-Smart Agriculture (CSA) has evolved into a mature and highly interconnected research domain anchored strongly in the broader discourse of climate change. The dominance of climate change as the central keyword across co-occurrence and density visualizations confirms that CSA is not treated as an isolated agricultural concept, but rather as an integrated response to global climate challenges. The strong linkage between climate change, food security, sustainability, and agriculture indicates that research in this field consistently frames agricultural transformation as both an adaptation and mitigation strategy. This reinforces the

original FAO conceptualization of CSA, which emphasizes productivity, resilience, and emission reduction as inseparable pillars.

The keyword clustering further demonstrates that CSA research operates along three primary intellectual streams: socio-economic resilience, environmental sustainability, and technological innovation. The socio-economic cluster highlights smallholder farmers, vulnerability, livelihoods, and adaptive management, underscoring that CSA research remains development-oriented and policy-relevant. This reflects the reality that climate impacts disproportionately affect smallholder systems in Sub-Saharan Africa and South Asia. The persistence of these themes across the network suggests that vulnerability reduction and resilience-building remain foundational priorities in CSA scholarship.

The environmental cluster emphasizes greenhouse gas emissions, soil health, carbon management, and crop systems. This indicates a strong mitigation-oriented dimension, particularly through soil carbon sequestration, improved nutrient management, and sustainable land use practices. The density visualization shows significant research concentration in emission-related themes, suggesting that CSA is increasingly aligned with global climate mitigation commitments such as the Paris Agreement. At the same time, the integration of crop-specific terms such as rice and maize highlights that mitigation research is grounded in staple crop systems critical to global food security.

Another important finding is the growing prominence of technological themes such as smart agriculture, precision agriculture, irrigation innovation, and agribusiness integration. The overlay visualization indicates that these themes are more recent compared to early adaptation-focused studies. This temporal shift suggests that CSA research is transitioning from vulnerability assessments toward solution-oriented, technology-enabled approaches. The convergence between CSA and digital agriculture reflects a broader transformation in agricultural research, where data-driven tools, remote sensing, AI-based decision systems, and precision input management are increasingly seen as essential instruments for climate resilience.

The co-authorship and country collaboration networks reveal that CSA research is highly international and strongly characterized by North–South and South–South partnerships. Countries such as India, the United States, Kenya, and Ethiopia play central roles, indicating that CSA research is both scientifically driven and development-focused. The strong representation of African countries in the collaboration network aligns with the vulnerability-based orientation of the field. Meanwhile, the presence of European institutions and global research centers demonstrates that CSA is supported by strong institutional frameworks and international funding mechanisms.

Institutional collaboration mapping highlights the central role of international agricultural research organizations, such as CGIAR-affiliated centers and leading agricultural universities. These institutions function as knowledge hubs, facilitating transnational research exchange and capacity building. The integration of global policy actors such as development banks further illustrates that CSA research is not purely academic but embedded in policy implementation and global sustainability agendas. This multi-level collaboration structure strengthens the translational impact of CSA knowledge into practice.

4. CONCLUSION

This bibliometric mapping demonstrates that Climate-Smart Agriculture research has evolved into a dynamic, globally interconnected, and increasingly interdisciplinary field centered on climate change, food security, and sustainable agricultural transformation. The analysis reveals a strong intellectual foundation built upon adaptation and resilience studies, which has progressively expanded toward integrated sustainability frameworks and, more recently, technology-driven solutions such as smart and precision agriculture. Collaboration networks highlight the pivotal

roles of major agricultural research institutions and countries from both the Global North and Global South, reflecting the policy relevance and development-oriented nature of the field. CSA research shows a clear trajectory from vulnerability assessment to innovation-oriented climate solutions, indicating that future progress will depend on strengthening interdisciplinary integration, technological accessibility for smallholders, and inclusive global research partnerships.

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