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Global Trends in Climate-Smart Agriculture Research in Publications from 2010 to 2024

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ABSTRACT

This study explores global trends in Climate-Smart Agriculture (CSA) research from 2010 to 2024, providing a comprehensive bibliometric analysis of publication growth, thematic evolution, and collaboration networks. The analysis reveals a significant shift in CSA research, with a growing focus on mitigation, technological innovations, and sustainable agricultural practices. Key themes such as soil carbon management, greenhouse gas emissions, and climate-resilient crops have emerged as central research areas, reflecting the growing need for climate adaptation and emission reduction strategies. The research highlights the leading roles of countries like India, China, and African nations such as Kenya, Ethiopia, and Malawi, in shaping CSA solutions. The study also emphasizes the increasing importance of international collaborations, which facilitate knowledge-sharing and the development of context-specific CSA practices. However, gaps in research remain, particularly in the areas of socioeconomic factors, policy frameworks, and scaling mechanisms for CSA adoption. Addressing these gaps is critical for ensuring the broader implementation and effectiveness of CSA strategies in the face of climate challenges.

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1. INTRODUCTION

Climate change poses one of the most significant threats to global agriculture in the 21st century. Rising temperatures, more frequent extreme weather events, and unpredictable rainfall patterns have already begun to destabilize traditional farming systems, reduce crop yields, and undermine food security worldwide. The agricultural sector itself is both a victim of and a contributor to climate change: it is highly vulnerable to climate impacts, yet it also accounts for a substantial share of greenhouse gas emissions globally [1]. In 2022, agrifood systems contributed about 37% of total emissions, with agriculture, forestry, and land-use sectors alone responsible for between 13% and 21% during 2010–2019—underscoring the dual challenge of sustaining agricultural productivity while mitigating environmental harm [2], [3].

In response to these mounting challenges, Climate-Smart Agriculture (CSA) has emerged as a pivotal framework over the last decade. First articulated around 2010, the CSA concept aims to transform agricultural systems so they are productive, resilient to climate impacts, and low in emissions where feasible, without compromising food security or livelihoods. The Food and Agriculture

Organization (FAO) defines CSA as an approach that supports agricultural stakeholders to respond strategically to climate change by sustainably increasing output, building resilience, and reducing greenhouse gas emissions. Similarly, institutions such as the World Bank promote CSA as an integrated landscape management strategy that addresses interlinked environmental and developmental challenges in agriculture [3], [4].

The conceptual appeal of CSA lies in its tripartite goals—productivity, adaptation, and mitigation—which align with broader international targets such as the Sustainable Development Goals (SDGs) and climate commitments under the Paris Agreement. Its adoption has been advocated at global, national, and local levels, especially among policymakers and development agencies seeking to fortify agricultural systems against climate vulnerability [5], [6]. Research efforts have focused on technologies, practices, and policies that integrate soil and water management, crop diversification, climate information services, and socio-economic incentives to support farmers' adaptive capacity.

Over time, CSA has also attracted interdisciplinary interest, spanning agronomy, climate science, economics, rural development, and environmental policy. Studies have examined CSA adoption barriers and enablers, the economic benefits of climate-resilient practices, and frameworks for scaling up effective interventions. For example, recent research highlights the role of institutional support, policy frameworks, and collaborative networks in enhancing CSA adoption among smallholder farmers in regions such as Southern Africa [7], [8]. Yet, despite this growing body of literature, scholars note that CSA's scientific definition and operationalization remain varied and context-dependent, reflecting the complexity of integrating climate resilience with agricultural sustainability goals.

In the past decade, scientific publications addressing Climate-Smart Agriculture have grown substantially, reflecting heightened global awareness of climate-related agricultural risks and the policy imperative for resilient food systems. Bibliometric and systematic reviews of CSA research show an upward trend in annual publications, international collaborations, and thematic diversification, suggesting a maturing but still evolving field of inquiry. By examining publication patterns from 2010 to 2024, scholars can gain insights into how academic attention has shifted over time, where research gaps persist, and how global research networks contribute to knowledge production on climate-resilient agricultural innovation.

Despite its increasing prominence, several critical challenges hinder a coherent understanding of global research trends in Climate-Smart Agriculture. First, there is no universally accepted definition and methodological framework for CSA across disciplines, resulting in heterogeneous research approaches and fragmented knowledge synthesis. Second, while some regions have developed robust research outputs and adoption strategies, other areas such as parts of Africa and Southeast Asia still exhibit limited research engagement or national investment plans for CSA. Third, existing literature reviews focus on specific geographic regions, thematic issues, or case studies, but comprehensive, global bibliometric analyses spanning the key period of CSA's diffusion (2010–2024) remain scarce. This gap inhibits systematic tracking of how research priorities have evolved in response to shifting climate dynamics, international policy frameworks, and emergent sustainability challenges. Consequently, the global research community lacks a consolidated evidence base to inform future scholarly directions, policy formulation, and strategic interventions in CSA. This study aims to analyze global trends in Climate-Smart Agriculture research publications from 2010 to 2024 by identifying patterns in publication growth, geographic and institutional contributions, thematic emphases, and collaboration networks.

2. METHOD

This study employs a bibliometric analysis to map the global trends in Climate-Smart Agriculture (CSA) research from 2010 to 2024. The bibliometric method allows for an objective, quantitative analysis of academic publications, enabling the identification of research patterns, key themes, and influential networks in CSA. The Scopus database was selected as the primary data source due to its comprehensive coverage of peer-reviewed journals, conference proceedings, and other scholarly publications across various disciplines. A detailed search query was developed, focusing on articles, reviews, and conference papers that specifically addressed CSA and its various dimensions, such as climate resilience, mitigation strategies, and sustainable agricultural practices. The search was filtered for publications between 2010 and 2024, and results were exported to a CSV format for further analysis.

For the analysis, the study utilizes VOSviewer, a powerful bibliometric visualization tool, to conduct citation and co-citation analysis. VOSviewer is specifically designed for the creation of visual maps that display relationships between publications, authors, keywords, and citations, making it ideal for analyzing research trends, institutional contributions, and thematic clusters. The tool will be used to generate visual networks that reflect the relationships between authors, institutions, and countries involved in CSA research, as well as to identify emerging topics and areas requiring further research. The results will provide a comprehensive overview of the evolution of CSA research, highlight gaps in current knowledge, and suggest future research directions to enhance the integration of climate-smart practices in global agriculture.

3. RESULT AND DISCUSSION

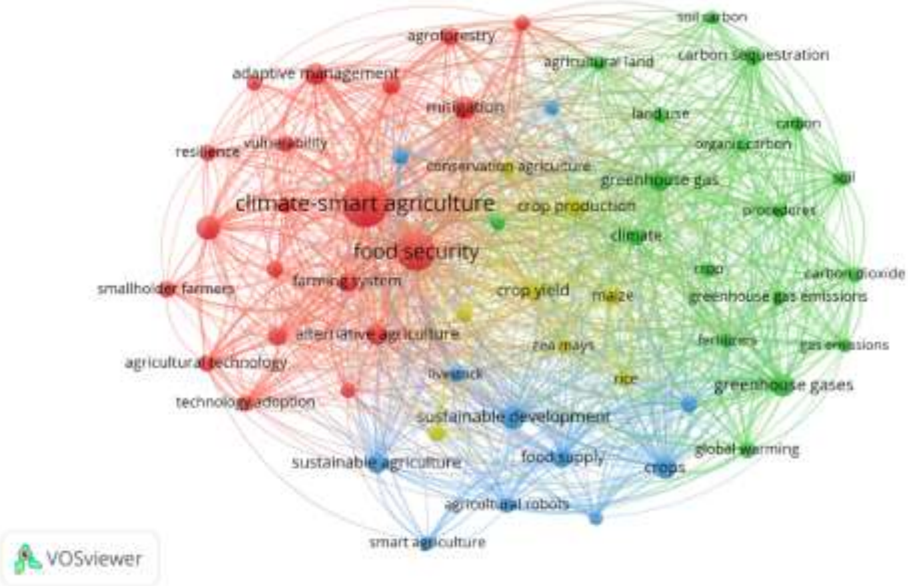

Figure 1. Network Visualization
Source: Data Analysis

Figure 1 shows a network map generated by VOSviewer, highlighting the key terms and their interrelationships in Climate-Smart Agriculture (CSA) research from 2010 to 2024. The map uses a co-occurrence analysis approach to identify the central themes and how frequently these themes are mentioned together in publications. The network contains clusters that represent specific areas of CSA, with different colors indicating different thematic groups. The largest and most prominent cluster is marked in red and includes terms like climate-smart agriculture, food security, vulnerability, adaptive management, and smallholder farmers. These terms are closely related to the core objectives of CSA: enhancing agricultural productivity while addressing the challenges posed by climate change. The significant size of this cluster shows that much of the CSA literature revolves around ensuring food security through climate adaptation strategies, particularly for vulnerable groups like smallholder farmers. This emphasizes the intersection of agricultural resilience and the ability to maintain food systems in the face of climate variability.

The green cluster highlights terms such as agricultural land, sustainable development, agriculture technology, agricultural robots, and technology adoption. This group focuses on the role of innovation and new technologies in transforming agriculture to be more sustainable and resilient to climate change. The prominence of agricultural technology and robotics indicates a rising interest in automation and precision agriculture as part of CSA solutions. These technologies are seen as essential for increasing agricultural efficiency and reducing emissions in line with CSA goals. A third distinct cluster is represented in blue, with terms such as mitigation, greenhouse gases, carbon sequestration, and soil carbon. This cluster focuses on the mitigation aspect of CSA, emphasizing strategies to reduce greenhouse gas emissions from agricultural practices and sequester carbon in soils. It also highlights the critical role of soil health and carbon management in achieving climate resilience. These terms are essential for understanding the environmental impact of agriculture and the potential for CSA practices to contribute to global climate mitigation efforts.

The yellow cluster emphasizes terms related to crop production, crop yield, maize, rice, and sustainable agriculture. These terms point to the importance of enhancing crop productivity under changing climatic conditions to ensure a stable food supply. The centrality of maize and rice suggests that these staple crops are often at the forefront of CSA discussions, particularly in regions where their production is threatened by climate change. Sustainable farming practices that improve crop yield while minimizing environmental impact are key themes in this cluster. The purple cluster connects terms such as global warming, sustainable agriculture, food supply, and climate change. This cluster highlights the interdisciplinary nature of CSA research, linking environmental concerns like global warming with agricultural sustainability and food security. It underscores the importance of addressing climate change at both global and local levels, with a focus on developing climate-resilient agricultural systems. The inclusion of terms like agricultural land and land use suggests an ongoing exploration of how to manage land more sustainably in response to climate challenges.

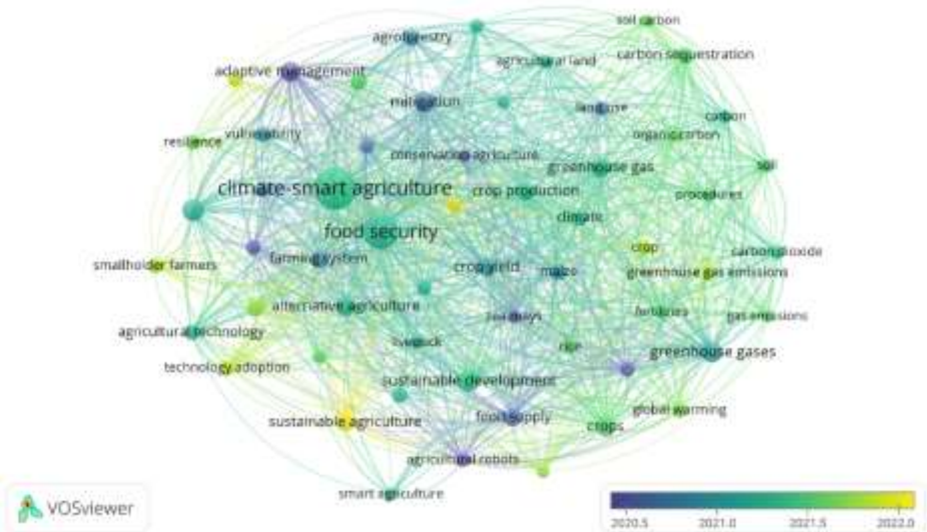

Figure 2. Overlay Visualization
Source: Data Analysis

Figure 2 represents the temporal evolution of research themes in Climate-Smart Agriculture (CSA), with the color scale indicating the publication year of related research articles. The blue color represents earlier publications (around 2020), while the yellow indicates more recent studies (from 2022). This visual depiction not only illustrates the clusters of related terms but also provides insights into the dynamics of research focus over the past few years. The clusters in this visualization highlight the shifting focus within CSA research. The green and cyan regions (associated with more recent studies) emphasize terms such as mitigation, carbon sequestration, greenhouse gases, and agricultural technology. These terms suggest a growing interest in technologies and practices that mitigate climate change, such as improving soil carbon storage and reducing greenhouse gas emissions from agriculture. The shift towards mitigation and sustainable practices aligns with global calls to reduce carbon footprints and increase the climate resilience of agricultural systems. The presence of agricultural technology and smart agriculture in more recent years signals the integration of cutting-edge innovations like agricultural robots, technology adoption, and precision farming into the CSA discourse.

Earlier research, indicated by blue and purple regions, focused heavily on food security, smallholder farmers, and farming systems. These foundational topics remain crucial, but as the research timeline progresses, the emphasis has gradually expanded to include climate adaptation strategies, resilience, and alternative agriculture. The appearance of terms like agriculture technology in the more recent years shows how the CSA field is evolving towards more technologically advanced solutions, whereas earlier research focused more on socio-economic aspects, such as ensuring food security for smallholder farmers in vulnerable regions. The clustering of terms like resilience and vulnerability in earlier research highlights a deep understanding of how climate change impacts agricultural systems, particularly in developing regions.

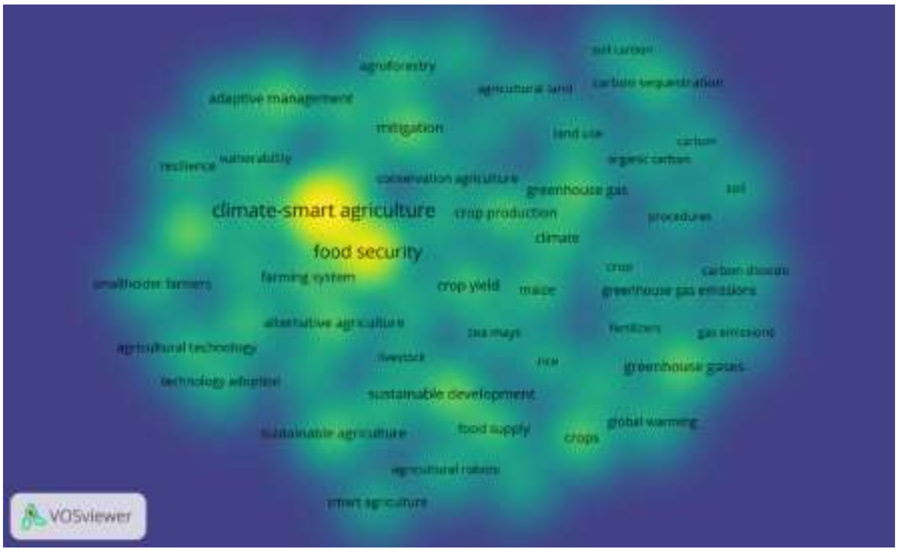

Figure 3. Density Visualization
Source: Data Analysis

Figure 3 highlights the concentration of research themes in Climate-Smart Agriculture (CSA) from 2010 to 2024, with a focus on the intensity of the terms. The brighter yellow region in the center represents the most prominent topics that are central to CSA research, such as climate-smart agriculture, food security, smallholder farmers, and farming systems. These terms appear to be the primary focus of the field, reflecting the importance of ensuring food security and supporting smallholder farmers in the face of climate change. Food security, specifically, is positioned as a central theme around which other terms like sustainable agriculture and technology adoption are clustered, suggesting that CSA research is largely driven by the need to develop agricultural systems that are both resilient to climate impacts and capable of ensuring long-term food security.

The heatmap also reveals the emergence of other important themes in CSA research, with terms like mitigation, agricultural technology, crop yield, greenhouse gases, and carbon sequestration appearing in varying shades of green and blue, indicating an increasing interest in climate change mitigation and the role of technological innovations in agriculture. The spread of these topics signifies a broader exploration of CSA, where there is growing research on reducing agricultural emissions and adopting sustainable farming technologies. The geographical spread in the map shows a shift towards integrating sustainable development and alternative agriculture, signaling the movement toward climate-resilient agricultural practices that reduce environmental impacts and enhance farm productivity.

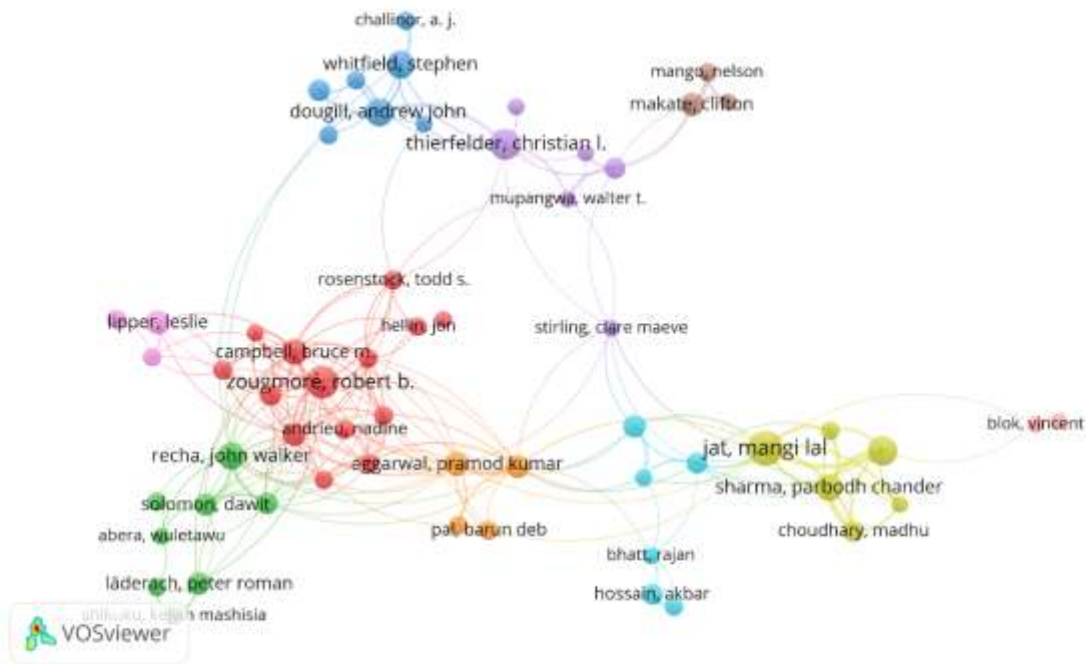

Figure 4. Author Visualization
Source: Data Analysis

Figure 4 hows a co-authorship network of researchers in the field of Climate-Smart Agriculture (CSA), with each node representing an author, and the connections between them indicating co-authorship relationships. The clusters of researchers (depicted by different colors) reveal significant collaboration networks within CSA research. For instance, the red cluster includes prominent authors like Bruce M. Campbell, Robert B. Zougmoré, and John Walker Recha, suggesting their central role in the development of CSA research, particularly in the context of climate adaptation and food security. Other clusters, like the green and blue groups, highlight authors focused on technological solutions and agriculture resilience. Authors such as Pramod Kumar Agarwal and Barun Deb Pal are linked with the broader themes of sustainable agriculture and climate change mitigation.

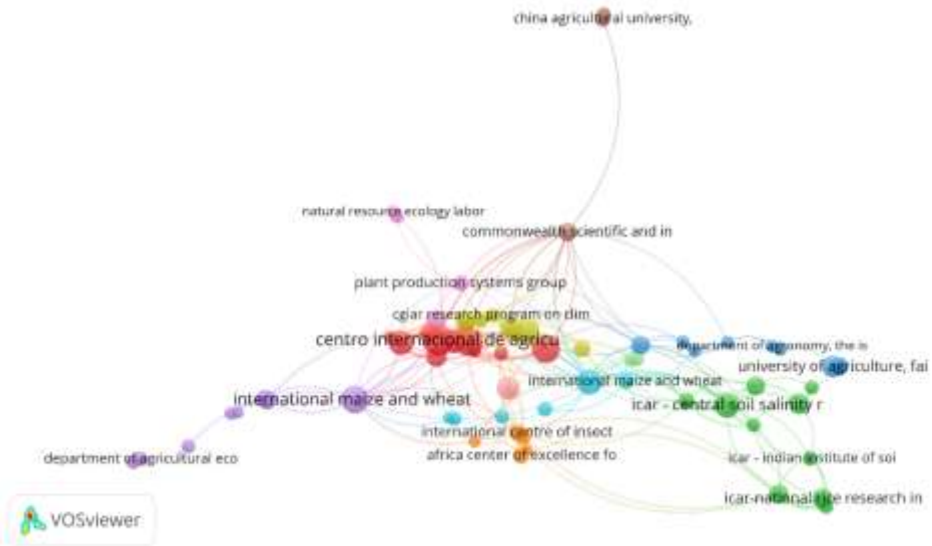

Figure 5. Institution Level Visualization
Source: Data Analysis

Figure 5 presents a collaboration network of institutions involved in Climate-Smart Agriculture (CSA) research, with each node representing an institution, and the connections between nodes showing collaborative relationships. The central cluster is dominated by Centro Internacional de Agricultura Tropical (CIAT), marked in red, which indicates a prominent role in global CSA research. CIAT is closely linked with other significant organizations such as the International Maize and Wheat Improvement Center (CIMMYT) and CGIAR Research Program, highlighting their key contributions to global agricultural research on climate adaptation and food security. The presence of institutions like China Agricultural University and University of Agriculture, along with ICAR (Indian Council of Agricultural Research), shows regional diversity, with both Asian and African centers being highly active in CSA research. The different colors in the visualization represent thematic areas within CSA, including agronomy, soil management, and plant production systems, underscoring the interdisciplinary nature of the field. This network illustrates the global collaboration dynamics that are fundamental to addressing climate challenges in agriculture.

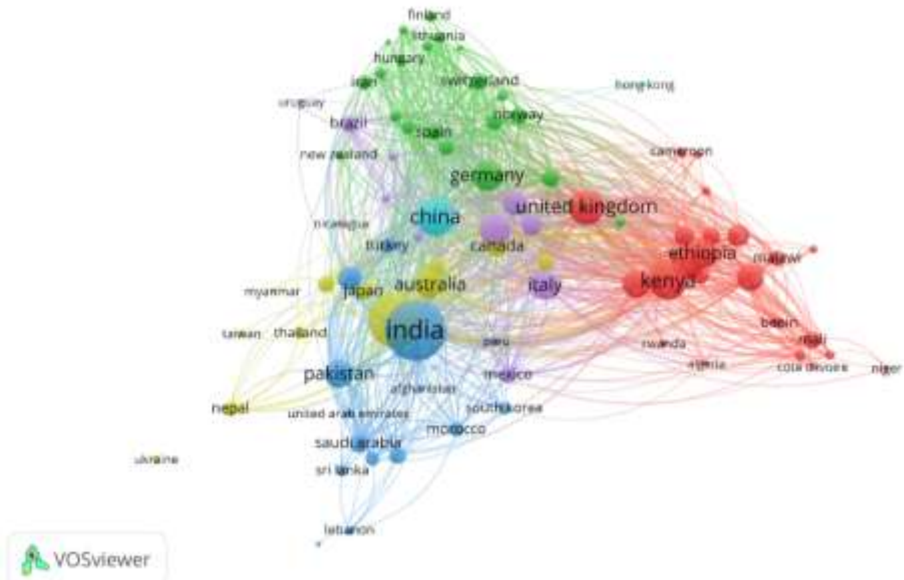

Figure 6. Country Level Visualization
Source: Data Analysis

Figure 6 represents the global collaboration network of countries involved in Climate-Smart Agriculture (CSA) research. The nodes (countries) are connected based on their co-authorship in CSA publications, with larger nodes indicating more central roles in the research landscape. The color-coded clusters reveal regional patterns: India and China dominate the blue and green clusters, reflecting their leading positions in CSA research, particularly in Asia. The red cluster is centered around Ethiopia, Kenya, and Malawi, highlighting the significant CSA research output in sub-Saharan Africa. These countries are critical as they face severe climate vulnerabilities, driving research focused on adaptation strategies in agriculture. The purple and yellow clusters show the involvement of European and Middle Eastern countries such as Germany, United Kingdom, and Saudi Arabia, indicating active research contributions across continents. This map highlights how global collaboration in CSA research is geographically diverse, with strong networks between countries in both developed and developing regions.

Table 1. Top Cited Literature

Citations	Authors and Year	Title
1,787	[9]	Climate-smart soils
1,563	[4]	Climate-smart agriculture for food security
1,444	[10]	Impact of climate change on crops adaptation and strategies to tackle its outcome: A review
1,121	[11]	Impact of climate change on agriculture and its mitigation strategies: A review
907	[12]	Soil structure and microbiome functions in agroecosystems
700	[13]	Digitalization to achieve sustainable development goals: Steps towards a Smart Green Planet
589	[14]	Soil salinity under climate change: Challenges for sustainable agriculture and food security
468	[15]	Sustainable intensification: What is its role in climate smart agriculture?
426	[16]	Barriers to the adoption and diffusion of technological innovations for climate-smart agriculture in Europe
371	[17]	Beyond conservation agriculture

Source: Scopus, 2026

Discussion

The bibliometric analysis of Climate-Smart Agriculture (CSA) research publications from 2010 to 2024 provides critical insights into the global research trends, collaboration patterns, and thematic developments in this vital area of study. One of the central findings is the growing emphasis on mitigation strategies and technological innovations. Over the past decade, CSA research has shifted from a foundational focus on food security and smallholder farmer support, as seen in earlier years, to a more advanced exploration of climate adaptation technologies and sustainable agricultural practices. The increasing prevalence of terms like agricultural technology, carbon sequestration, and greenhouse gas emissions in recent publications highlights the substantial role that technological solutions now play in addressing climate change within agricultural systems.

The rise of sustainable development as a focal theme in CSA research also aligns with global calls for climate resilience and low-carbon agriculture. This trend reflects an intersection of agricultural practices with global environmental sustainability goals, particularly as countries face mounting challenges from climate change. The integration of agriculture and environmental science in CSA research is evident in the expansion of themes such as soil management, resilience, and climate-smart technologies. The growing interest in smart agriculture, including innovations such as agricultural robots and precision farming, underscores the desire to harness cutting-edge technologies to enhance productivity and sustainability in an increasingly unpredictable climate.

Furthermore, the geographical distribution of CSA research, as revealed by the collaboration network and publication analysis, emphasizes the significant contributions of both developing and developed regions. Countries in Africa, particularly Kenya, Ethiopia, and Malawi, show a pronounced focus on CSA due to the direct threat posed by climate variability to food systems and livelihoods. Their research priorities largely align with adaptation strategies and resilient agricultural practices. In contrast, countries like India and China are leading in both climate mitigation and technological adaptation research. These regions are investing heavily in climate-resilient crops, soil carbon management, and emission reduction practices, which are central to their agricultural sectors.

The collaboration map also reveals an increasing trend toward international cooperation, with China, India, and European countries (such as Germany and the United Kingdom) forming strong research alliances. These international collaborations enhance knowledge-sharing and bring together diverse perspectives, ensuring that CSA solutions are adapted to various regional contexts. This global cooperation is particularly vital in overcoming common challenges in CSA research, such as the lack of data in low-resource settings, unequal access to technologies, and the need for context-specific solutions to climate impacts on agriculture. However, the study also reveals several research gaps that need to be addressed in future studies. While much of the CSA literature focuses on agronomic solutions, there is a significant underrepresentation of socioeconomic factors and policy integration in research. The role of policy frameworks and institutional support in scaling up CSA practices remains underexplored. Moreover, while technological innovation is central to CSA, more research is needed to understand the social acceptability and economic feasibility of these technologies, especially for smallholder farmers who face significant barriers to adoption. Similarly, climate finance and adaptation funding mechanisms are critical components of scaling CSA practices but are often overlooked in research.

4. CONCLUSION

This study on global trends in Climate-Smart Agriculture (CSA) research from 2010 to 2024 provides valuable insights into the evolution of the field, highlighting the shift towards mitigation, sustainable development, and technological innovations. Over the past decade, CSA research has increasingly focused on climate resilience, agricultural productivity, and emission reduction, with significant contributions from both developed and developing countries. The study reveals that Africa, particularly Ethiopia, Kenya, and Malawi, has become a key region for CSA research, driven by the need to adapt to climate-induced food security challenges. At the same time, countries like India and China are leading in mitigation technologies and climate-smart practices. The findings also underscore the importance of international collaborations, which are fostering knowledge-sharing and ensuring that CSA solutions are tailored to diverse regional contexts. However, there remain critical gaps in understanding the socioeconomic impacts, policy frameworks, and scaling mechanisms necessary for wider adoption of CSA practices. Addressing these gaps will be essential for advancing CSA research and ensuring its effectiveness in building sustainable, climate-resilient agricultural systems worldwide.

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