Bibliometric Analysis of Climate-Smart Agriculture: Trends, Research Gaps, and Impacts on Crop Production

Vivian A. Segobre
West Visayas State University, College of Agriculture and Forestry
Lambunao, Iloilo, Philippines

ABSTRACT Climate-Smart Agriculture (CSA) plays a critical role in combating climate change, ensuring food security, and promoting sustainable crop production. This study conducts a bibliometric analysis of CSA research from 2015 to 2024, leveraging data from the Scopus database. The analysis pursues three main objectives: (1) examining research trends by tracking publication growth, subject areas, and document types; (2) identifying gaps in research by evaluating the distribution across countries, institutions, and funding sources; and (3) proposing directions for future research. Using a Boolean search string ("climate-smart agriculture" OR "CSA" OR "climate resilient agriculture" OR "sustainable agriculture") AND ("bibliometric analysis" OR "scientometric analysis" OR "systematic mapping" OR "literature review" OR "science mapping") AND ("crop production" OR "crop yield" OR "agricultural productivity" OR "farming systems"), data were retrieved from titles, abstracts, and keywords. After screening, 111 documents were retained for analysis, with bibliometric graphs and outputs generated directly from Scopus to ensure precision. Results show a consistent growth in CSA research, with a notable surge in 2024. Environmental Science (24.4%) and Agricultural and Biological Sciences (20.9%) emerged as the dominant fields, while the study also highlighted CSA's interdisciplinary nature, with contributions from Social Sciences, Computer Science, and Energy. India, the United States, and China led in research output, supported by robust institutional and funding networks. However, significant gaps remain in Africa and Latin America, with a scarcity of studies focused on socio-economic aspects and policy development. To propel CSA towards greater impact, it is crucial to foster collaborations, expand regional participation, and diversify funding sources, thereby advancing sustainable crop productivity and climate resilience globally.

Keywords: advanced agriculture, crop products, impact, resiliency, sustainability

Introduction

Agriculture plays a crucial role in ensuring food security, economic development, and rural livelihoods worldwide. However, the sector faces increasing challenges due to climate change, which exacerbates extreme weather events, disrupts food systems, and threatens crop productivity (FAO, 2013). Rising global temperatures, unpredictable rainfall patterns, prolonged droughts, and more frequent pest and disease outbreaks have intensified the need for sustainable agricultural practices that enhance resilience and mitigate adverse environmental impacts. In response, Climate-Smart Agriculture (CSA) has emerged as an innovative approach that integrates strategies to increase agricultural productivity, enhance adaptation to climate change, and reduce greenhouse gas emissions (Lipper et al., 2014). The adoption of CSA involves various techniques, including improved soil and water management, agroforestry, conservation agriculture, climate-resilient crop varieties, and precision agriculture technologies (Rosenstock et al., 2019). These practices contribute

to enhancing food security while ensuring environmental sustainability. However, despite the growing body of literature on CSA, there remains a need for a systematic evaluation of its research landscape to understand dominant themes, assess knowledge gaps, and analyze its impact on crop production.

Bibliometric analysis provides a structured and data-driven approach to examining research trends by assessing publication patterns, identifying influential authors and institutions, and mapping scientific collaborations (Donthu et al., 2021). Recognizing influential authors is not merely for academic ranking; it is important because their contributions often shape the direction of research, establish thematic priorities, and foster international collaborations. Understanding these leading voices helps highlight where innovations emerge and where future research may be directed. At the same time, bibliometric analysis is most valuable in uncovering research gaps, areas where evidence is limited or underexplored. This is critical for guiding future studies and maximizing the practical contributions of CSA to sustainable agriculture. Specifically, this research will examine how CSA research has progressed over time, determine key contributors in the field, explore dominant research themes related to crop production, analyze global research collaborations, and, most importantly, highlight gaps that need to be addressed to strengthen CSA's role in agricultural sustainability.

The principles of CSA align with several United Nations Sustainable Development Goals (SDGs). CSA plays a crucial role in achieving SDG 2 (Zero Hunger) by promoting sustainable agricultural practices that improve food security and crop resilience in changing climatic conditions (FAO, 2013). It also directly supports SDG 13 (Climate Action) by advocating climate adaptation and mitigation strategies that reduce the vulnerability of farming communities to climate-related threats (Vermeulen et al., 2012). Additionally, CSA aligns with SDG 15 (Life on Land) by encouraging sustainable land management, soil conservation, and biodiversity-friendly agricultural practices (Lal, 2016). By examining the scientific landscape of CSA through bibliometric analysis, this study aims to support the global agenda for sustainable agriculture and climate resilience by identifying research gaps and areas requiring further innovation and investment.

Accordingly, this study seeks to conduct a bibliometric analysis of climate-smart agriculture (CSA) research with the following specific objectives: (1) to analyze research trends in CSA by examining patterns in publication growth, subject areas, and document types; (2) to identify research gaps by assessing the distribution of studies across countries, institutions, and funding sources, highlighting underrepresented regions and themes; and (3) to outline future research directions based on the trends and gaps revealed in the analysis. By addressing these objectives, this study will contribute to a deeper understanding of CSA research, providing valuable insights for scientists, policymakers, agricultural practitioners, and funding agencies. Ultimately, it will serve as a strategic tool for enhancing the adoption of CSA practices, improving crop productivity, and fostering climate-resilient agricultural systems globally.

Methodology

This study employed a bibliometric analysis to examine research trends, thematic areas, and scientific impacts of Climate-Smart Agriculture (CSA) in relation to crop production. Bibliometric analysis, as a quantitative approach, enables the systematic evaluation of research by assessing publication growth, citation performance, collaboration patterns, and keyword distribution, thereby providing insights into the development and direction of scientific inquiry within a particular domain.

The data were collected from the Scopus database, which was selected because of its wide coverage of peer-reviewed journals and high reliability as a bibliographic source. To retrieve relevant publications, a Boolean search string was constructed with the aid of ChatGPT and refined according to the study objectives. The final search string used was: ("climate-smart agriculture" OR "CSA" OR "climate resilient agriculture" OR "sustainable agriculture") AND ("bibliometric analysis" OR "scientometric analysis" OR "systematic mapping" OR "literature review" OR "science mapping") AND ("crop production" OR "crop yield" OR "agricultural productivity" OR "farming systems"). This search was applied to article titles, abstracts, and keywords, covering the publication period from 2015 to 2024, to capture recent advancements and contemporary perspectives in CSA research.

The initial search generated a total of 111 documents. Each record was carefully screened to ensure accuracy and relevance. Duplicate entries were checked using document titles, DOIs, and EIDs (unique Scopus identifiers). The screening confirmed that there were no duplications, and therefore all 111 documents were retained for analysis. No restrictions were placed on document type and language, ensuring broad inclusivity of relevant studies. However, the search was limited to the years 2015–2024 to capture recent research trends and developments." The bibliographic information of these documents, including authors, titles, abstracts, keywords, source titles, publication year, and citation counts, was exported from Scopus in CSV format to facilitate analysis.

For the data analysis, only the bibliometric graphs and outputs generated directly from Scopus were used. These visualizations were examined to identify publication trends, influential authors and institutions, research collaboration patterns, thematic foci, and emerging knowledge gaps in the field of CSA and crop production. The interpretation of Scopus-generated outputs allowed for the extraction of insights regarding the growth of CSA-related research, its global distribution, and its contribution to enhancing crop resilience and sustainability. Since this study exclusively relied on secondary data from published literature indexed in Scopus, ethical approval was not required.

Results and Discussion

Documents by Year

The results show a clear upward trajectory in the annual publications related to Climate-Smart Agriculture (CSA) from 2015 to 2024 (Figure 1), underscoring a significant rise in research activity within this field. From 2015 to 2019, the number of publications remained relatively low, with fluctuations below 10 documents per year. In 2020, there were 8 publications, followed by a slight dip to around 4 publications in 2021. However, a

steady increase is seen from 2022 to 2023, indicating a growing recognition and emphasis on CSA research.

The most notable shift comes in 2024, when publications surged to over 50 documents. This sharp increase not only highlights a considerable rise in research output but also emphasizes the growing urgency and critical importance of CSA in tackling the dual challenges of climate change and food security. This trend suggests a shift in the academic and global focus, potentially fueled by increased funding, international collaborations, and an expanding recognition of the pressing need for climate-resilient agricultural practices.

The surge in CSA-related publications signals a heightened global awareness of the interconnectedness between agriculture, climate change, and food security. As more research emerges, it implies that the agricultural sector is increasingly being recognized as a key player in climate change mitigation and adaptation strategies. This increasing body of research could catalyze policy development and guide the implementation of more sustainable and adaptive farming practices worldwide. Furthermore, the rising research activity may encourage greater investment from both public and private sectors in climate-smart innovations, potentially leading to more rapid technological advancements in the field.

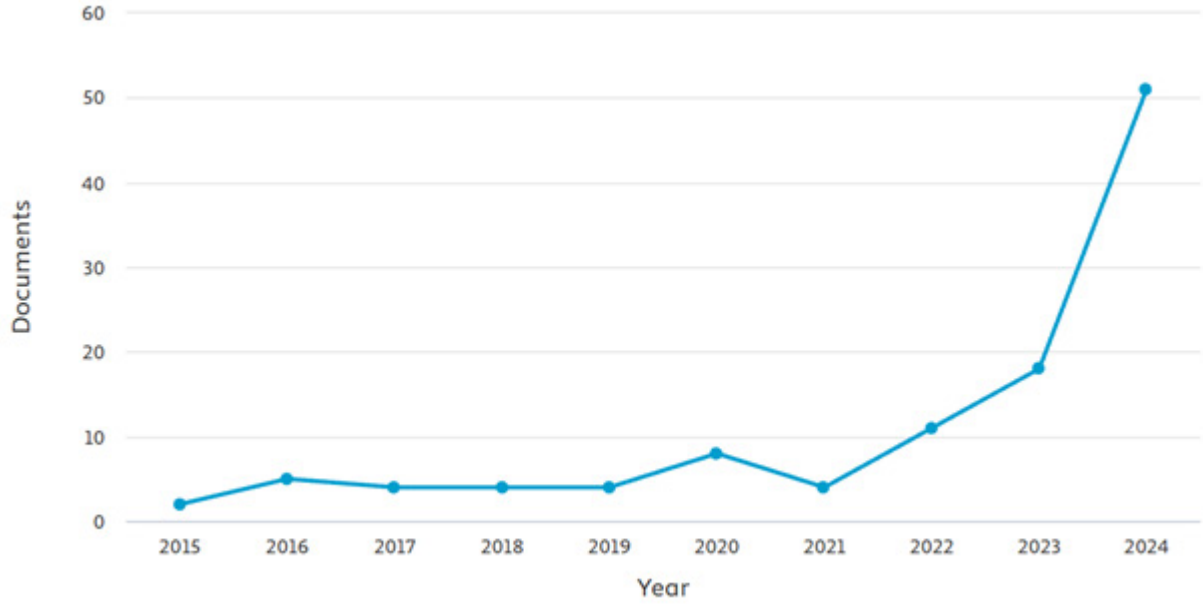


Figure 1. Annual trend of document publications (2015–2024).

Documents per Year by Source

The figure illustrates the trends in document publication by source over time from 2016 to 2024, highlighting the varying publication patterns across different sources (Figure 2). "Microbiological Research" remained constant, publishing one document per year throughout the entire period. "Agronomy for Sustainable Development" showed a slight increase from one document in 2016 to two documents in 2020, maintaining a steady output thereafter. "Sustainability Switzerland" exhibited a more dynamic trend, increasing from one document in 2018 to three documents by 2021, remaining stable until 2022, then decreasing to two documents in 2023, and finally peaking at four documents in 2024. "Frontiers in Sustainable Food Systems" started publishing in 2022 with one document and gradually increased to two documents in 2024, while "Water Switzerland" also started

publishing in 2022 with one document and gradually increased to two documents by 2024. The varying trends across these sources suggest different levels of focus and activity in CSA-related research within each publication outlet. Publications like "Microbiological Research" and "Agronomy for Sustainable Development" have shown a more consistent and stable output, indicating sustained but relatively less dynamic research activity in these journals. In contrast, journals like "Sustainability Switzerland," "Frontiers in Sustainable Food Systems," and "Water Switzerland" have exhibited more fluctuation, potentially reflecting shifts in the relevance of specific CSA topics over time, or changing editorial focuses in response to emerging global issues.

The fluctuations in publication trends across these journals imply diverse research priorities within the field of CSA. Journals like "Sustainability Switzerland" and "Water Switzerland," which have seen more pronounced variations in publication frequency, may be responding to urgent global challenges such as water scarcity, sustainability in agriculture, and the integration of ecological systems with agricultural practices. The steady output from "Microbiological Research" may suggest ongoing, foundational research into the microbiological aspects of CSA, providing crucial insights for climate-resilient agriculture. The trends also point to the evolving role of CSA research in addressing climate change, with some sources reflecting a greater alignment with contemporary environmental concerns, while others maintain a steady focus on long-term sustainable practices.

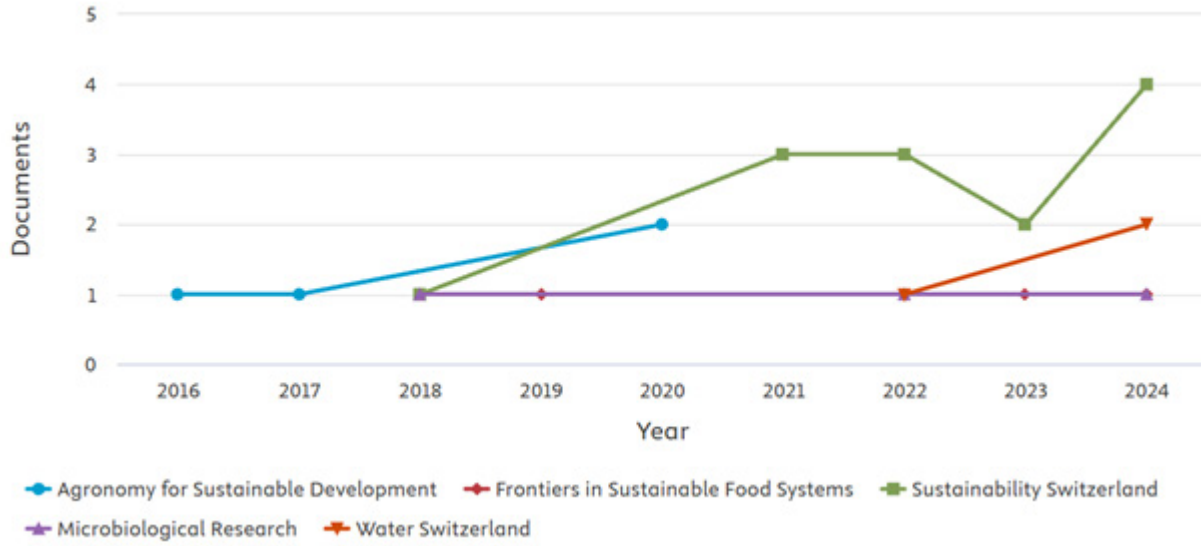


Figure 2. Trends in document publication by source over time.

Documents by Author

The figure presents the number of research documents authored by the top contributors in climate-smart agriculture (Figure 3). Cortner, O., El Bilali, H., Garrett, R.D., Gil, J.D.B., Indrasti, R., Kumar, A., and Wezel, A. lead with 2 documents each, indicating a strong research focus and influence in the field. Their consistent contributions underscore their pivotal roles in shaping the discourse on climate-smart agriculture.
Following these leading authors, A. Diuana, F. Abawiera Wongnaa, C., and Abbasi, E. have contributed with 1 document each. This distribution suggests a concentration of research output among a few key authors, while others have made fewer contributions. It may

imply that a select group of researchers is driving the most impactful studies in the field, potentially influencing policy and practice.

The data highlights the contributions of individual researchers to the body of knowledge on climate-smart agriculture. The varying levels of contribution reflect different research interests, expertise, and engagement within the field. However, the concentrated contributions may also suggest a need for increased collaboration and diversity of voices to broaden the scope of research. It may be valuable for emerging researchers to engage with this core group of contributors to foster innovation and explore unexplored areas within climate-smart agriculture. Expanding the pool of active contributors could further enhance the depth and breadth of solutions to address climate change challenges in agricultural practices.

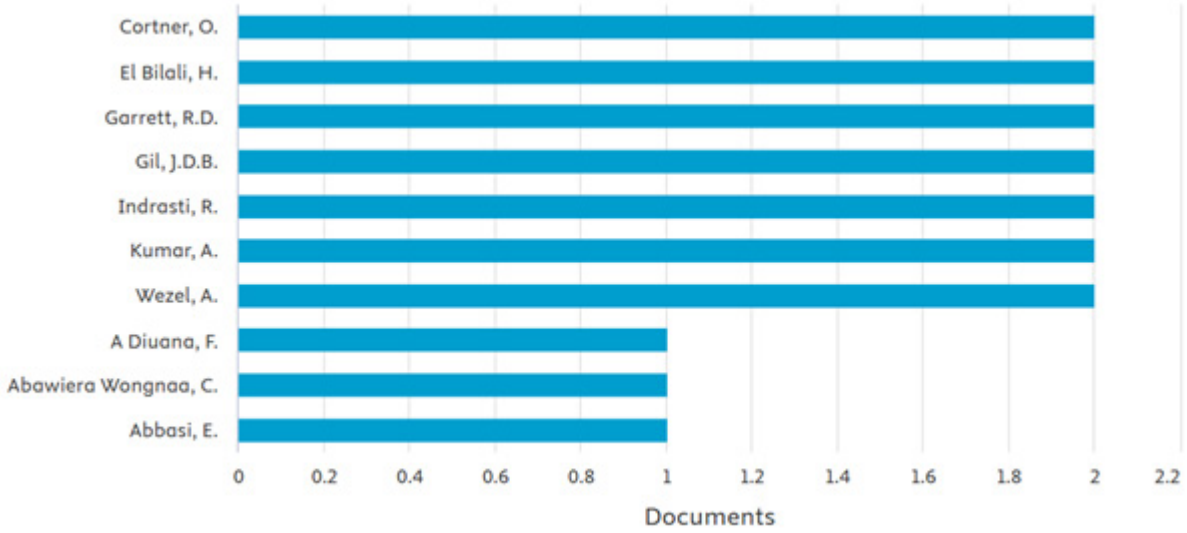


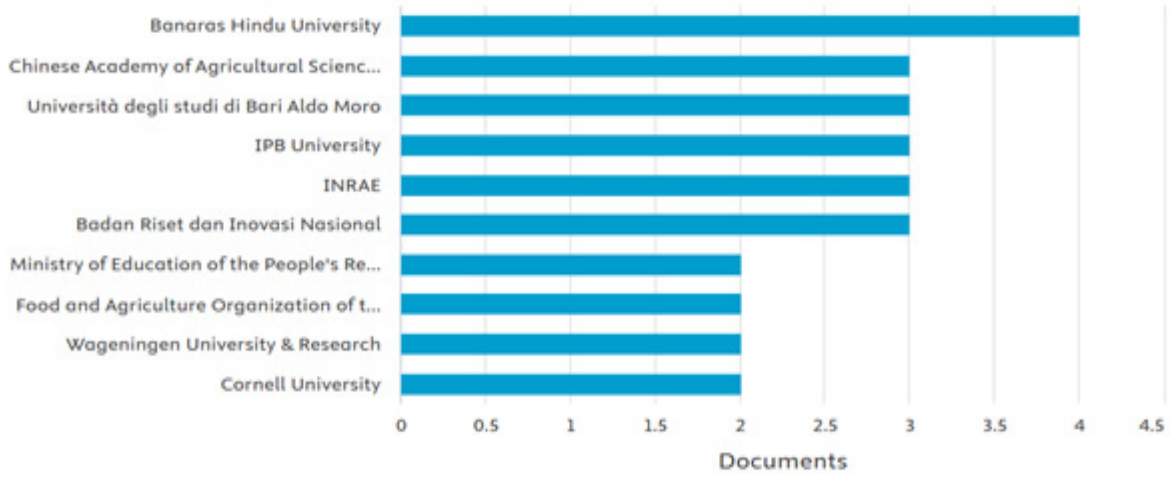
Figure 3. Leading authors in climate-smart agriculture research.

Documents by Affiliation

The figure illustrates the number of research documents produced by various academic and research institutions focusing on climate-smart agriculture (Figure 4). Banaras Hindu University leads with the highest number of contributions, indicating a strong institutional commitment to advancing agricultural sustainability and climate adaptation research. This suggests that Banaras Hindu University is not only a leader in the field but also plays a central role in shaping the direction of future agricultural practices, potentially influencing both policy and practice at a global scale.

Following Banaras Hindu University, the Chinese Academy of Agricultural Sciences, Università degli studi di Bari Aldo Moro, IPB University, INRAE, and Badan Riset dan Inovasi Nasional have a comparable number of publications. The presence of these institutions reflects a diverse geographical distribution and widespread interest in developing sustainable agricultural strategies. This broad participation implies that climate-smart agriculture is a global priority, with research collaboration across continents contributing to a shared understanding of local and regional challenges.

Other institutions, such as the Ministry of Education of the People's Republic of China, Food and Agriculture Organization of the United Nations, Wageningen University & Research, and Cornell University, also contribute significantly to the body of knowledge on climate-smart agriculture. The data emphasizes the importance of global research efforts in addressing agricultural sustainability challenges and highlights the key roles played by various institutions in advancing scientific knowledge in this domain. This widespread engagement implies that collaborative research efforts will be crucial in developing scalable and adaptable solutions to the pressing challenges posed by climate change to global food systems. These efforts could also lead to more informed policy recommendations and innovations that foster resilience in agricultural systems worldwide.



Documents by Country or Territory

The figure presents the number of research documents published on climate-smart agriculture by country, highlighting the leading contributors in this field (Figure 5). India ranks first with the highest number of publications, exceeding 20 documents, indicating its strong research focus on sustainable agricultural practices. The United States follows with 16 documents, reflecting its active engagement in addressing climate-related agricultural challenges. China ranks third with 14 documents. Italy and the United Kingdom contribute around 9 documents each, demonstrating Europe's growing involvement in sustainability research. Indonesia has 8 documents. Brazil and France contribute around 7 and 6 documents, respectively, showing significant interest in climate-smart farming solutions. South Africa and Australia each contribute a smaller number of publications, suggesting emerging but relatively limited research efforts in these countries.

The data underscores a global interest in climate-smart agriculture, with India, the United States, and China leading the research output, likely due to their large agricultural sectors and vulnerability to climate change. The varying contributions from other countries suggest potential research gaps, particularly in smaller or developing economies, which may lack the infrastructure or resources to conduct large-scale agricultural studies. These gaps highlight the need for targeted investments in agricultural research capacity in underrepresented regions to help mitigate the challenges posed by climate change. Additionally, the disparities in research output could limit the development of context-specific solutions for sustainable farming in these regions.

The findings imply that global collaboration is essential to address these gaps. International partnerships could help share knowledge, resources, and innovations that could benefit regions with less research activity. The implications for policy-makers include the need for fostering greater cooperation between countries and institutions, improving funding mechanisms, and promoting capacity-building initiatives that focus on underserved regions. This would not only enhance global research efforts but also drive more inclusive and sustainable agricultural practices, ultimately contributing to global food security and climate resilience.

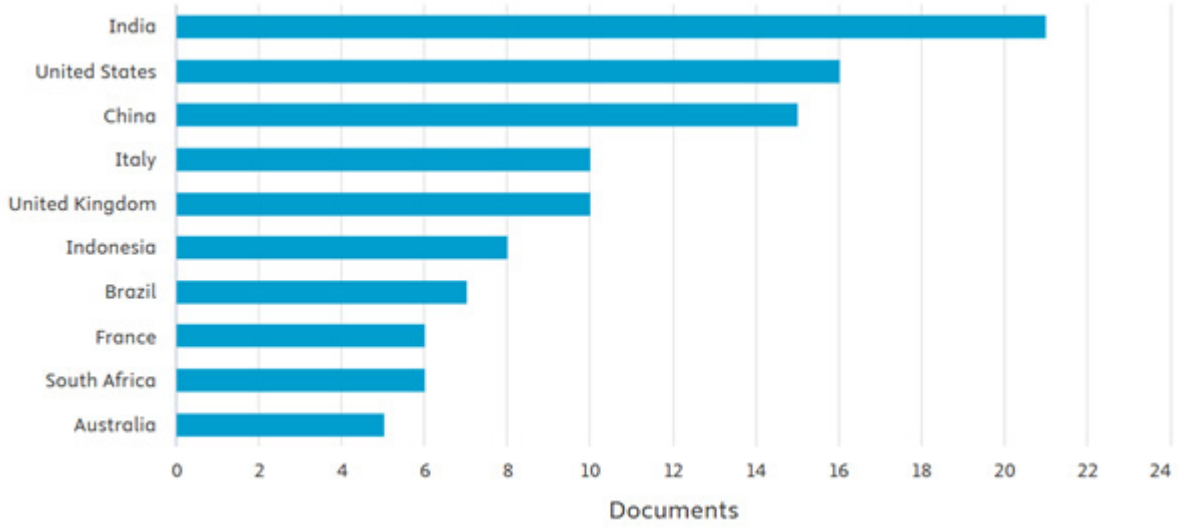


Figure 5. Global contributions to climate-smart agriculture research by country.

Documents by Type

The results show that research publications on climate-smart agriculture are predominantly focused on literature reviews (56.8%) and original empirical articles (32.4%), with a smaller proportion of conference papers (8.1%) and book chapters (2.7%). This distribution suggests that the field is primarily concerned with synthesizing existing knowledge and generating new empirical findings, which are crucial for guiding policymakers and practitioners in the effective implementation of climate-smart agricultural practices. However, the lower proportion of conference papers and book chapters indicates a gap in real-time discussions and in-depth, comprehensive explorations of the topic. The substantial presence of review articles and empirical studies reflects the growing demand for detailed knowledge and innovations in the field. Implications of these findings include the need for more dynamic academic exchanges through conferences to encourage real-time dialogue, as well as an emphasis on book chapters to provide comprehensive, interdisciplinary discussions.

While empirical research remains essential for advancing practical solutions, the lack of more diverse document types may suggest areas for future development, particularly in fostering broader engagement and providing comprehensive resources for both the academic community and field practitioners. Overall, these findings highlight the importance of a balanced approach to climate-smart agriculture research, one that integrates both in-depth knowledge synthesis and ongoing, real-time research discussions.

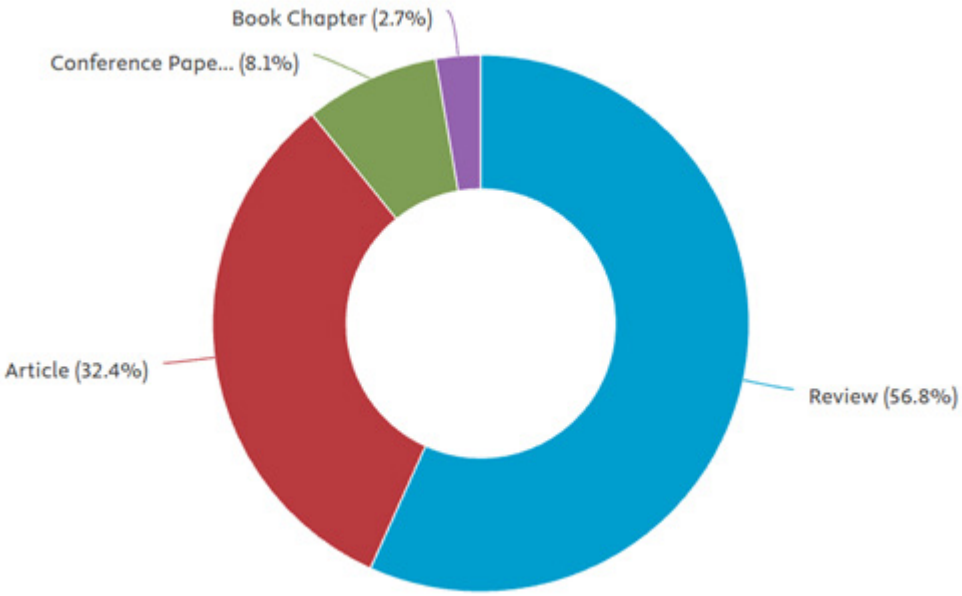


Figure 6. Distribution of climate-smart agriculture research by document type.

Documents by Subject Area

The figure illustrates the distribution of Climate-Smart Agriculture (CSA) research by subject area, showing the multidisciplinary character of the field (Figure 7). Environmental Science accounts for the largest share at 24.4%, underscoring the strong emphasis on environmental dimensions of CSA, particularly climate change mitigation, adaptation, and resource management. Agricultural and Biological Sciences follow closely at 20.9%, reflecting the central role of core agricultural research in advancing CSA practices. Social Sciences contribute 11.5%, highlighting the importance of addressing farmer behavior, adoption, and policy frameworks. Computer Science, at 9.0%, points to the growing use of digital tools, modeling, and precision agriculture in CSA, while Energy (7.3%) indicates links to renewable energy and sustainable resource use.

Other subject areas contribute smaller shares but add to the diversity of CSA research. Biochemistry, Genetics, and Molecular Biology account for 4.3%, supporting advances in crop improvement and resilience. Engineering contributes 3.8%, reflecting technological innovations, while Immunology and Microbiology (3.4%) and Medicine (2.6%) emphasize health and biosecurity aspects. Earth and Planetary Sciences (2.1%) show a minimal but relevant connection to climate and ecosystem studies. The "Other" category, at 10.7%, further reinforces the interdisciplinary reach of CSA.

The distribution implies that while CSA research is firmly rooted in environmental and agricultural sciences, there is growing recognition of the need to integrate social, technological, and energy perspectives. However, the relatively smaller share of socio-economic, policy, and health-related studies suggests a gap that must be addressed to ensure CSA strategies are not only scientifically sound but also socially inclusive, technologically adaptive, and relevant to the broader challenges of climate resilience (Figure 7).

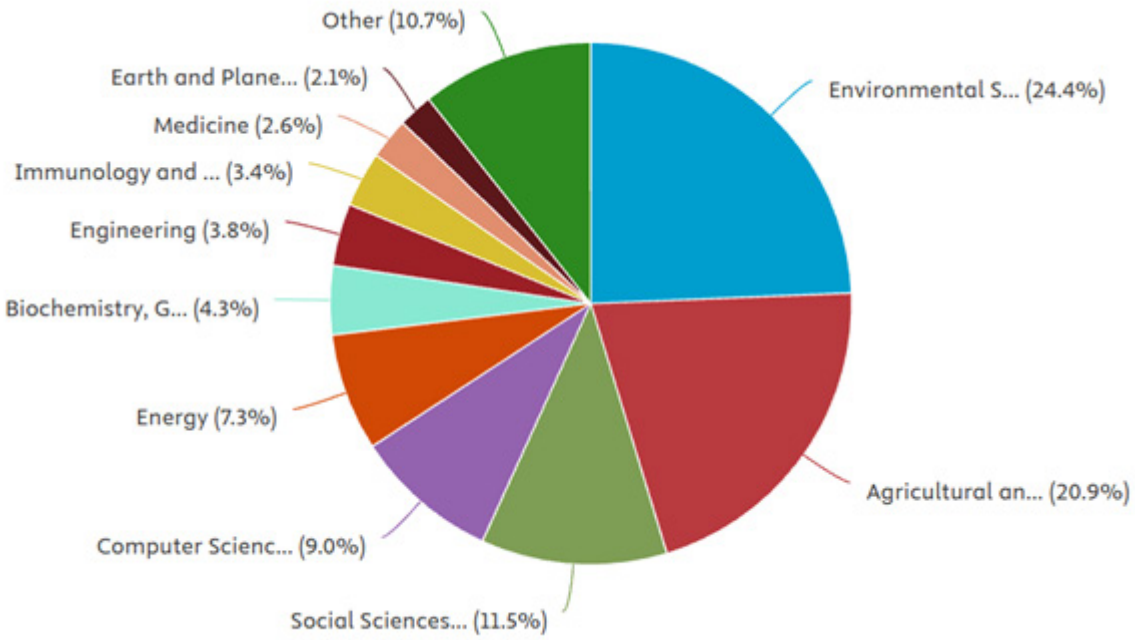


Figure 7. Distribution of climate-smart agriculture research by subject area

Documents by Funding Sponsor

The figure presents the distribution of research documents based on their funding sponsors (Figure 8), highlighting key organizations contributing to climate-smart agriculture studies. The National Natural Science Foundation of China is the leading funding source, supporting the highest number of research documents, indicating China's strong commitment to advancing research in sustainable agriculture and climate adaptation strategies. The National Key Research and Development Program of China follows closely.

Other significant contributors include the Consortium of International Agricultural Research Centers, the European Commission, and the Horizon 2020 Framework Programme, reflecting international and European investment in climate-smart agricultural initiatives. The National Institute of Food and Agriculture, the National Science Foundation, and the U.S. Department of Agriculture also contribute substantially, demonstrating the United States' engagement in this field.

The Bill and Melinda Gates Foundation and the Council of Scientific and Industrial Research have a relatively lower number of documents compared to the leading funding sponsors. The dominance of Chinese and international funding agencies highlights the global focus on climate-smart agricultural research. However, the varying contributions from different sponsors suggest potential funding gaps and the need for increased investment in specific areas or regions that may require greater international collaboration. Strengthening global funding networks can enhance research efforts, particularly in regions most vulnerable to climate change impacts on agriculture, informing future research directions.

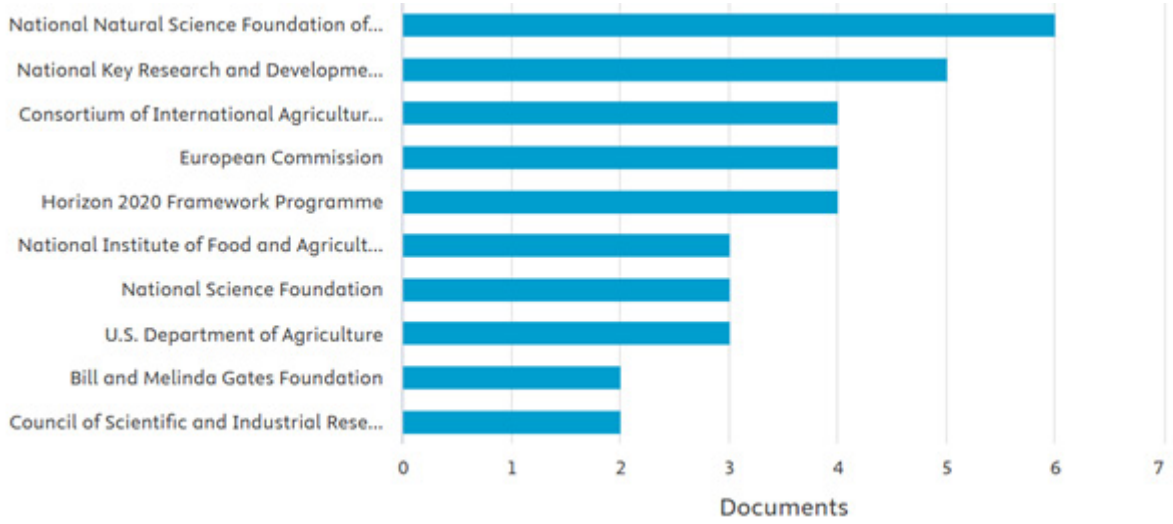


Figure 8. Major funding sponsors supporting climate-smart agriculture research.

Conclusions

The study reveals a consistent growth in climate-smart agriculture (CSA) research since 2015, reaching its peak in 2024, with a significant concentration of publications in journals like Sustainability (Switzerland). The research landscape is predominantly shaped by journal articles and agronomic/environmental studies. However, the distribution of research outputs is uneven, with Asia and Europe leading the charge, while Africa and Latin America remain notably underrepresented. Additionally, funding and authorship are concentrated within a small group of institutions, scholars, and sponsors, further exacerbating the imbalance. These trends underscore the need for a more inclusive and diverse approach to CSA research, highlighting the importance of engaging underrepresented regions and promoting interdisciplinary collaboration. To enhance the relevance and impact of CSA research, it is crucial to increase funding opportunities, encourage cross-disciplinary studies, foster global collaborations, and actively involve researchers from underserved regions. By doing so, CSA research can become more equitable, practical, and globally relevant, ensuring that advancements in the field address the needs of all communities and are grounded in real-world applications.

Declaration by Author
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