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EXPLORING THE SCIENTIFIC NEXUS: GLOBAL TRENDS IN CLIMATE CHANGE AND AGRICULTURAL RESEARCH FROM 2000 TO 2024

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ABSTRACT

Climate change poses a serious challenge to international economic growth, as it adversely affects food security and farmers' ability to produce sufficient food amid changing climatic conditions. As a means of addressing this challenge, the authors have critically analysed the existing literature related to the topic from the period of 2000 to 2024, specifically focusing on climate change in relation to agriculture. The focus of this literature review is to identify the trends regarding climate change and agricultural production, and also to report on how the main article title of "The Impact of Climate Change on Agriculture" has changed over time through the conduct of a bibliometric analysis. Several databases were used to collect information for this review, including the Web of Science (WoS), and the PRISMA framework was followed to allow for proper inclusion of articles and sufficient thoroughness of discussion. The review indicates that recent years (from 2014 onward) have seen a rapid increase in the number of publications related to climate change and agriculture, and the United States has produced the highest number of corresponding authors and also the highest total number of publications (4,039) for the study period, while China ranks second with approximately 2,781 publications. According to the results of the bibliometric analysis, the top contributing authors were Müller C, Liu Y, and Lobell DB. It was found that the Key terms frequently appeared in the literature include 'agriculture', 'climate change', and 'impacts'. This research is vital for understanding the existing knowledge, identifying research gaps, research directions and focuses, evaluating sources and credibility, developing theoretical frameworks, supporting arguments and analysis in climate change and sustainable development, and providing invaluable insights for researchers, policymakers, and Practitioners.

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1. INTRODUCTION

Climate refers to the long-term generalized weather pattern of a particular region. The United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as a shift in climate patterns primarily caused by human activities that alter the global atmosphere. In contrast, the Intergovernmental Panel on Climate Change (IPCC) uses a broader definition, including any climate shift over time, regardless of whether itis due to natural or human factors (Roger and Pielke, 2004). Several researchers from different parts of the world have revealed that climate change has become a major threat to agricultural productivity (Jat et al., 2019; Scherr et al., 2012; Lipper et al., 2014; de Pinto et al., 2020; Saj et al., 2017). Agriculture is the cornerstone of human civilisation, providing food, fibre, and livelihoods for billions of people worldwide. The vulnerability of agricultural activities is different from region to region. Specifically, developing countries are highly vulnerable (Lipper et al., 2014; Kurukulasuriya & Rosenthal, 2021) due to a high rate of agricultural dependency and limited technological adaptation (Yohannes, 2016). Scientific evidence confirms that human-caused greenhouse gas emissions are driving global warming, directly impacting agricultural production (Zhao et al., 2023). For instance, deforestation, increased greenhouse gas emissions, and pollution have led to a 0.9°C increase in global temperature since the 19th century, potentially reaching 1.5°C by 2050, causing more extreme weather events (Arora, 2019). Over the past 150 years, the global average temperature has increased, with approximately 40% of this increase occurring over the last three decades. This rise in GHGs leads to more extreme weather, deadly heat, and severe droughts, significantly threatening agriculture by reducing farm income and land value (Zhao et al., 2023). The significant temperature rise would have a major effect on crop yields, and its inherent sensitivity to weather and climate variations underscores this vulnerability (Singh & Singh, 2017). As a consequence, climate change has become a major issue that has a serious impact on food security (Lipper et al., 2014;Kangogo et al., 2021; Tankha et al., 2020; Zaidi et al., 2024 ; Kurukulasuriya & Rosenthal, 2021; Yohannes, 2016; Ho & Shimada, 2019; Barasa et al., 2021 ; Adamides, 2020; Onyeneke et al., 2021; Zougmoré et al., 2018; Akinsemolu et al., 2024; Arora, 2019; Belay et al., 2024; Brouziyne et al., 2018; Dinesh et al., 2018; Malhi et al., 2021; Okolie et al., 2023; Singh & Singh, 2017; Zhao et al., 2023). The challenges posed by climate change to agriculture are diverse, including shifts in temperature and precipitation patterns, extreme weather events such as floods and droughts, and rising sea levels. However, predicting the full range of climate change impacts on agriculture is difficult due to its dependency on factors such as precipitation, temperature, and carbon dioxide fertilization. (Lipper et al., 2014; Karimi et al., 2018; Yohannes, 2016). Furthermore, these changes are compounded by evolving pest and disease dynamics, fluctuations in atmospheric carbon dioxide levels, and alterations in the nutritional composition and growing seasons of crops (Kurukulasuriya & Rosenthal, 2021; Yohannes, 2016; Adamides, 2020; Okolie et al., 2023; Jat et al., 2019). When people are forced to migrate or experience severe droughts, farmland is often abandoned, exacerbating the problems as soil nutrients become immobilized and salt accumulation increases (Arora, 2019). On the other hand, the water shortages associated with climate change exacerbate drought-related stress on agriculture, lead to inconsistent irrigation supplies, and reduce the predictability of farm planning (Kurukulasuriya & Rosenthal, 2021; Karimi et al., 2018; Yohannes, 2016). These conditions also caused damage to crops, resulting in lower yields and compelling farmers to adapt or modify their practices (Mathews et al., 2018; Khatri-Chhetri et al., 2017). Further, the occurrence of extreme floods has increased by 50% over the past decade, representing a fourfold rise compared to the two preceding decades. Rising sea levels or intense rainfall threaten farming in coastal areas by making the soil salty and stressing crops, which ultimately puts our food supply at risk (Arora, 2019). These impacts may vary, but urgent action is needed to address challenges of climate change and its effects on agriculture (Zaidi et al., 2024; Yohannes, 2016; Okolie et al., 2023; Singh & Singh, 2017).

In the present context, Climate-Smart Agriculture (CSA) is a sustainable approach to addressing global food security to enhance agricultural productivity (Das & Ansari, 2021; Hellin & Fisher, 2019; Lou et al., 2024; Mathews et al., 2018; Mwongera et al., 2017; Raihan et al., 2024; Scherr et al., 2012; Belay et al., 2024). Climate Smart Agriculture serves as a comprehensive approach that necessitates decision-maker interventions at all levels to build resilient agricultural systems, safeguard, and prevent both current and future food shortages by integrating various sustainable farming practices (Lipper et al., 2014; Adamides, 2020). It integrates sustainable techniques such as conservation tillage and agroforestry (Scherr et al., 2012). It refers to agricultural practices that aim to increase productivity and income, enhance farm resilience, and mitigate climate change by reducing greenhouse gas emissions (Kangogo et al., 2021; Lipper et al., 2014; Ho & Shimada, 2019; Mizik, 2021; de Pinto et al., 2020; Everest, 2021; Onyeneke et al., 2018; van Wijk et al., 2020; Williams et al., 2015).

The literature review has emerged as one of the most common methods used to analyse the impacts of climate change on agriculture. For instance, Yohannes (2016) and Karimi et al. (2018) examined the effects of climate change on agriculture and the current adaptation efforts made by governments and farmers through literature-based analysis (Cuéllar Lugo et al., 2023). This study aims to systematically review scientific literature on agricultural impacts and climate change published over the past decade. In 2021, Mizik conducted a literature review to systematically map the current state of climate-smart agriculture practices on small-scale farms. This analysis examined the specific practices and the factors that influence and the rate at which farmers adopt them (Zhang et al., 2017) , highlighting the crucial role of additional climatic variables beyond just temperature and precipitation by analysing Chinese county-level agricultural data from 1980 to 2010. Specifically, humidity and wind speed are vital for crop growth due to failing to include these variables when forecasting climate change's impact on crop yields can lead to biased predictions. Mendelsohn, (2008) examines multiple studies quantifying the substantial impact of rising temperatures on these farms. Despite potential adaptive measures, significant agricultural losses are anticipated in developing countries throughout the coming century. Further, Tankha et al. (2020) reported a case about irrigation techniques that can contribute to climate change mitigation and adaptation on three complementary approaches: institutional, sociological, and technical. The Onyeneke et al. (2021) study analyses the determinants of farmers' climate change perception and their adoption of CSA, and principal component analysis and multivariate probit regression were established. Yang et al. (2023) analysed Web of Science literature from 1990 to 2021, using bibliometric tools (COOC, VOS viewer, Cite Space) to map research evolution, hot topics, and future directions. Similarly, Wu et al. (2023) conducted a bibliometric analysis of over 3,000 peer-reviewed papers published between 1996 and 2022. Their work provides a comprehensive overview of the research's status, focus, networks, and funding, highlighting the dramatic increase in scientific inquiry driven by the complex effects of climate anomalies on agriculture, especially global warming. It is worth mentioning that most of researches has collected data through semi-structured interviews and focus group discussions (Okoronkwo et al., 2024; Nkumulwa & Pauline, 2021), in-depth interviews (Ho & Shimada, 2019). (Okoronkwo et al., 2024) has analysed data using descriptive statistics and principal component analysis using a Varimax rotated matrix. Adamides(2020) conducts a structured literature review to examine the application of advanced agricultural technologies, focusing on robotics, IoT (Internet of Things), and remote sensing for CSA because of its capability to achieve optimal farm performance by enhancing sustainable, high-yield, and profitable farming. Developing nations are particularly vulnerable, as their low-latitude farms often contend with already scorching temperatures.

The CSA seeks to improve farm resilience, revenue, productivity, and climate change mitigation by lowering greenhouse gas emissions (de Pinto et al., 2020; Ho & Shimada, 2019; Kangogo et al., 2021; Lipper et al., 2014; Mizik, 2021; Onyeneke et al., 2018). Research supports CSA methods by emphasising how they can help with climate adaptation, boost agricultural productivity, and provide sustainable food and income sources (Belay et al., 2024). CSA-oriented bibliometric research has been conductedto a limited extent. By applying a comprehensive bibliometric analysis of climate-smart strategy, Wang et al. (2024) examined the correlation between CSA and food loss management, and Okolie et al. (2023) analysed the relationship between CSA and farm productivity in the studies published between 2009 to 2022. Luckyardi et al. (2022) utilised bibliometric analysis alongside descriptive statistics. Both Luckyardi et al. (2022) and Morkūnas et al. (2022) have used VOSviewer software to find out the landscape of CSA research. Zaidi et al.'s (2024) research investigates the progress of CSA studies from 2012 to 2023, using both bibliometric mapping and literature review of Elsevier Scopus data. In the same way, the bibliometric analysis has been conducted by utilising the Scopus database (Pang et al., 2023; Safeer et al., 2024). Pang et al. (2023) extract the high-frequency word and phrase analysis using bibliometric approaches, and Safeer et al. (2024) analyse the development of IoT and blockchain technologies within precision agriculture.

This study offers a unique bibliometric analysis of climate change and agriculture research trends from 2000 to 2024. In contrast to previous studies, this study mainly focused on climate change and agricultural research trends and also identified knowledge gaps and future research directions. By synthesising interdisciplinary research, this review aims to deepen understanding of climate change and sustainable agriculture development, providing crucial insights for researchers, policymakers, and practitioners.

2. METHODOLOGY

The methodology used in this research has been described in five categories based on an adaptation from the PRISMA structure as described below: 1. Database and coverage 2. Search methodology 3. Criteria for inclusion and exclusion 4. Tools used 5. Data analysis..

Database and coverage: For the purposes of this study, a systematic quantitative method was employed to thoroughly evaluate academic publications associated with agriculture and climate change. The Web of Science (WoS) Core Collection was selected as the primary source of data due to its extensive database of high-quality peer-reviewed journal publications, as well as the development of an extensive citation index, making it a high-quality source for conducting bibliometric analyses. Within the existing literature, only publications indexed within the WoS-based database published between 2000 and 2024 were considered for the purposes of this study. The initial search yielded 12,004 documents related to the impact of climate change on agriculture.

Search methodology: Search methodology consisted of applying various search techniques, including keyword searches, language restrictions, publisher dates, level of relevance, and type of publication, to refine the total number of published works searched from 12,004 to 6,500 English Language Publications. The English Language Publications were further broken down by publication type (i.e., original research, review publications, chapters in books, and conference proceedings), and only the types of publications that were appropriate for the analysis in this paper were utilised. The majority of the articles (6283) were published as original research articles; the only other types of published articles (book chapters (n = 6), data papers (n = 8), early-access articles (n = 88), proceedings articles (n = 113)) were the lesser numbers of published works. There were also two retrospective articles among the published works, as classified by the Web of Science document type categories.

Tools used: Various tools were utilised for both extracting and filtering data throughout this comprehensive bibliometric data journey. Bibliometrix (the R version of Biblioshiny under the Bibliometric package) and VOSviewer are the two primary software programmes that facilitated both the analysis and visualisation of this bibliometric data. The statistical component of Biblioshiny was used to identify the frequency of co-occurring keywords and, therefore, to identify and quantify many interrelated aspects of various systems related to the complexity of our co-occurring keywords (Baidya & Saha, 2024). All bibliographic data downloaded from WoS were saved in .txt format, regardless of the final download format, and any necessary changes would be made so that the downloaded files could be processed and visualised.

\The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) modified framework was used as the guiding principle in compiling the list of eligible publications. The primary goals of the PRISMA framework are to provide users with full transparency, reproducibility, and methodological rigor while at the same time limiting the amount of potential selection bias during the choice of the literature to be included in the final database. To be classified as relevant to this research project, a record must be located in the WoS database, dated between 2000 and 2024, and must contain a direct connection to the core research topic by the keywords used in the article, as well as through the title and abstract. Any record or publication that does not meet any of these minimum criteria will be excluded from consideration as an eligible record or publication for bibliometric analysis due to not having sufficient bibliographic data to be properly analysed or indexed as part of bibliometric analysis. To have consistency and improve data quality, non-scholarly documents, which consist of any documents that are not published in academic journals, such as corrections, notes, editorial material, and unrelated types of documents, are eliminated from the analysis.

Analytical and presentation approach: The analysis of both the research and the results of this paper is presented using a combination of descriptive statistics, co-authorship, keyword co-occurrence, citation analysis, and thematic evolution analysis. A co-occurrence analysis of the keywords was conducted using the “author keywords” as the unit of analysis. The full counting method was used in the analysis. In order to facilitate visualisation, a minimum number of keyword occurrences was required, and a thesaurus file was used for merging of related terms and elimination of non-informative words. A VOS mapping approach was adopted, (in which nodes represented keywords and links indicated their co-occurrence, with link strength proportional to the frequency with which the keywords co-occurred.). Clustering analysis was conducted via VOSviewer software, which resulted in the formation of clusters according to specific themes, each having a unique color.

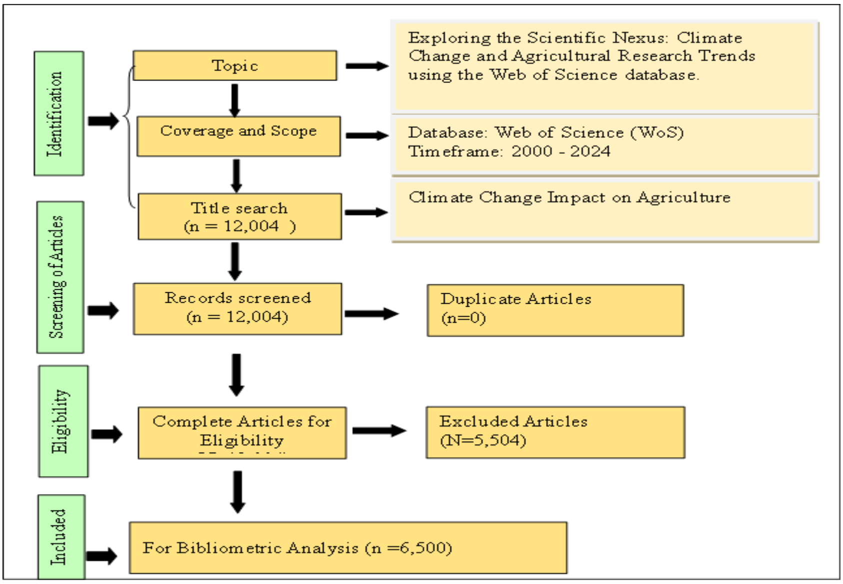

Figure 1: PRISMA-Modified Framework

3. RESULTS

3.1 Publication Profile and Longitudinal Trends

In the year 2000, the total number of articles published started off at around 25 per year and fluctuated for a number of years before transitioning to a period of consistent and accelerating growth in article publication. For the first time in the year 2010, the quantity of articles published exceeded 100, with 109 articles being published that year and continuing to increase into the year 2017, where they reached 309 articles published during the year. The greatest increases in published articles appear to occur in the last several years, from 388 published articles in 2019 to 581 published articles in 2020, and 1,004 published articles in 2024.

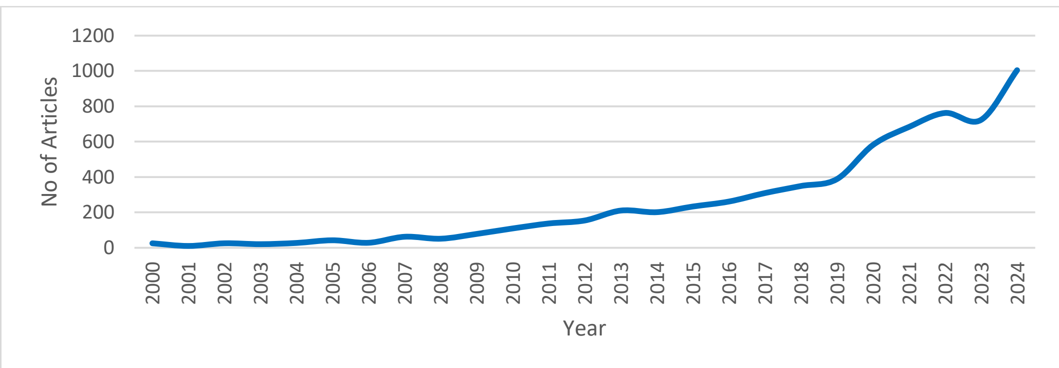

Figure 2: Yearly Scientific Outputs on Climate Change and Agricultural Production

According to Figure 3, the analysis of the production from countries from 2000 to 2024 reveals distinct trends of growth in the number of products produced by each of the countries represented in the table. The US ranks first in terms of total output for all years, it had less than 100 products in 2000, and its production increased to a peak of 4,039 products. China is the second largest producer, producing 2,781 products, with its growth following a similar point of accelerated growth after the year 2015. The UK and Germany have experienced steady growth as well, with the production of 1,263 articles from the UK and 1,127 from Germany. India is closely behind with 1,029 articles. The other countries in the top 10 are Australia (891), France (626), Italy (602), Canada (536), and Spain (532). While the UK, Germany, and India all exhibited similar growth curves for a significant portion of the study period, the data show that the dynamic research environment globally is primarily due to increased production from North America and Asia.

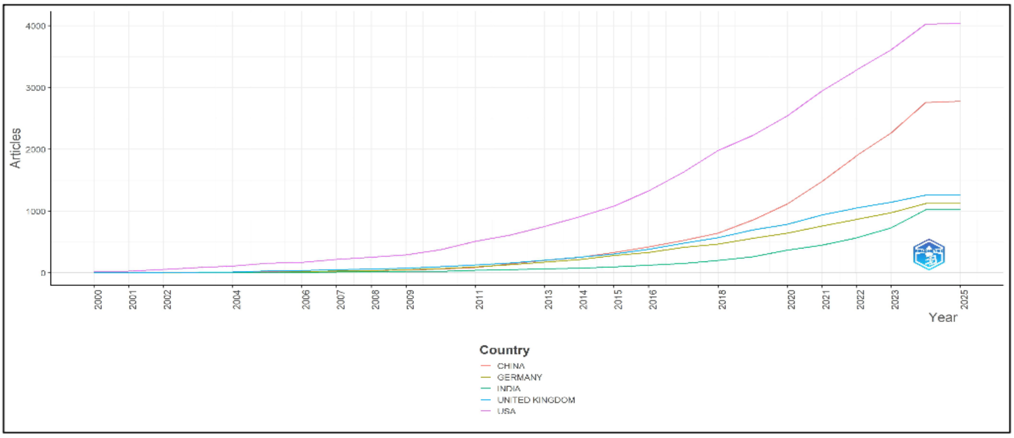

Figure 3: Country-Specific Scientific Outputs on Climate and Agriculture ((It is important to note that the number of publications per country includes more than one country for an article; hence, the sum for all countries is higher than the total number of documents in the database).

Initially, all countries exhibited relatively low and similar levels of article production. However, over the years, a significant divergence occurred, with the USA showing the most substantial increase, particularly after 2010, reaching over 4,000 articles by 2024. China also experienced a dramatic surge in article production starting around 2015, reaching the second-highest level by 202 Germany and the United Kingdom showed a more gradual and relatively similar upward trend in article production, while production in India increased steadily but remained lower than the other three leading countries, the USA, China, and the United Kingdom, throughout the period. The reasons may be several key factors, primarily related to differences in research funding, infrastructure, and institutional priorities. (Chai et al., 2019) support with the statement that a significant shift has occurred in global agricultural and food R&D spending. Using a purchasing power parity (PPP) basis, China has surpassed the USA both public and private sector investment. This indicates a major rebalancing of financial power within the sector, with China emerging as a new leader in agricultural innovation.

3.2 Disciplinary and Journal-Based Analysis

The most prominent journals that published the research papers in the concerned field during the study period are Climate Change, Sustainability, Science of Total Environment, Environmental Research Letters, and Agricultural Systems. All five journals showed upward trends of publications in the relevant field throughout the whole period. However, there is a significant change in the Sustainability journal products published by MDPI, which showed a remarkable achievement in 2024, publishing 248 articles, which is the highest number of articles recorded in that particular year. "Climate Change' was the leading journal in this particular field, publishing the highest number of research papers in the field until 2024. However, suddenly, journal sustainability achieved a sharp upward trend of publications, overtaking Climate change in 2024. Journal Sustainability started this upward trend in 2013 and reached its maximum in 2024. Another notable change is evident between Environmental Research Letters and Science of the Total Environment journals. From 2012 to 2020, the second highest publisher was Environment Research Letters, and Science of the Total Environment held the third or fourth position from time to time. However, the figures indicate a sudden rise in publications in the Science of the Total Environment Journal, becoming the third highest publisher in 2024 in this particular field (Figure 4).

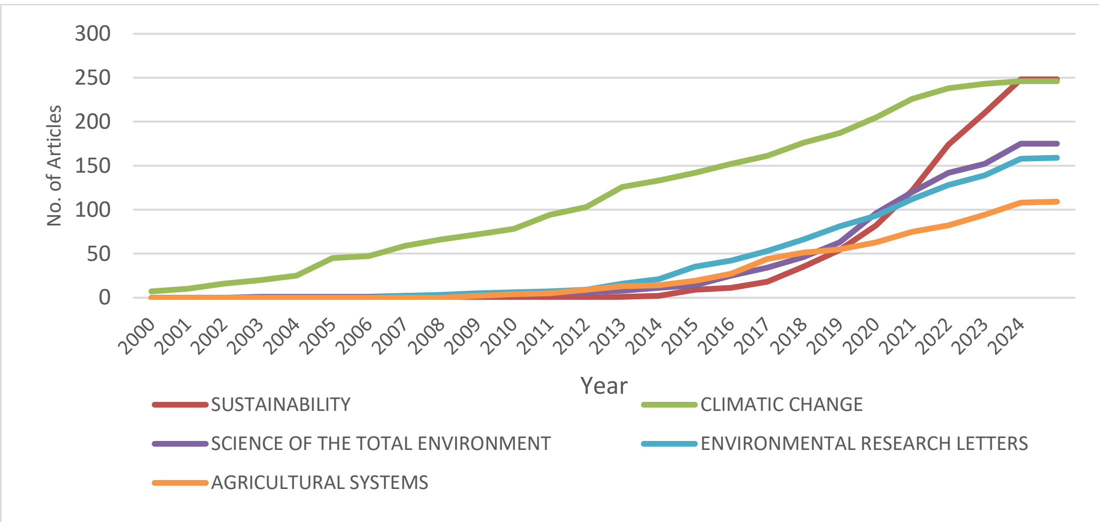

Figure 4: Yearly Bibliometric Production by Source

3.3 Geographic and Institutional Contributions

Table 1 presents a comparative distribution of article production across ten leading countries. The USA leads with the highest number of articles at 1,089, representing 16.8 percent of the total, and out of that, 777 are single-country publications (SCP), and 312 are multiple-country publications (MCP). China has produced 875 articles (13.5%), having 499 SCP and a higher proportion of MCP at 43 per cent (376 articles). India, the United Kingdom, and Germany have progressively fewer total articles, with India having a smaller percentage of MCP (21%), while the UK and Germany show a higher proportion of MCP at 56.5 per cent and 54.1 per cent, respectively. Australia, Italy, Canada, Spain, and France have the lowest total article counts, with varying percentages of MCP, ranging from France's 53.4 per cent down to Canada's 37.5per cent. Overall, the table highlights the dominance of the USA and China in article production and provides insights into the distribution between single- and multiple-country publications for each nation (Figure 5).

Table 1: Articles published by countries (based on corresponding author affiliations)

COUNTRY	ARTICLES	ARTICLES %	SCP	MCP	MCP %
USA	1089	16.8	777	312	28.7
CHINA	875	13.5	499	376	43
INDIA	381	5.9	301	80	21
UNITED KINGDOM	333	5.1	145	188	56.5
GERMANY	318	4.9	146	172	54.1
AUSTRALIA	263	4.0	135	128	48.7
ITALY	195	3.0	119	76	39
CANADA	176	2.7	110	66	37.5
SPAIN	166	2.6	90	76	45.8
FRANCE	146	2.2	68	78	53.4

Note: SCP – Single Country Publication, MCP – Multiple Country Publication

Further examining the contributions of affiliations to this field of study, several key trends emerge. The Chinese Academy of Sciences stands out with the highest number of publications (705) (Table 2). Followed by CGIAR (405) and the United States Department of Agriculture (USDA) (220). The University of California System (283) and Wageningen University and Research (242) also demonstrate significant contributions. In addition to the above top contributors, there are a few more affiliations that play a significant role, including the Commonwealth Scientific and Industrial Research Organization (CSIRO) with 188 publications, the Indian Council of Agricultural Research (ICAR) with 166 publications; all these publishers count below 200 publications (Table 2).

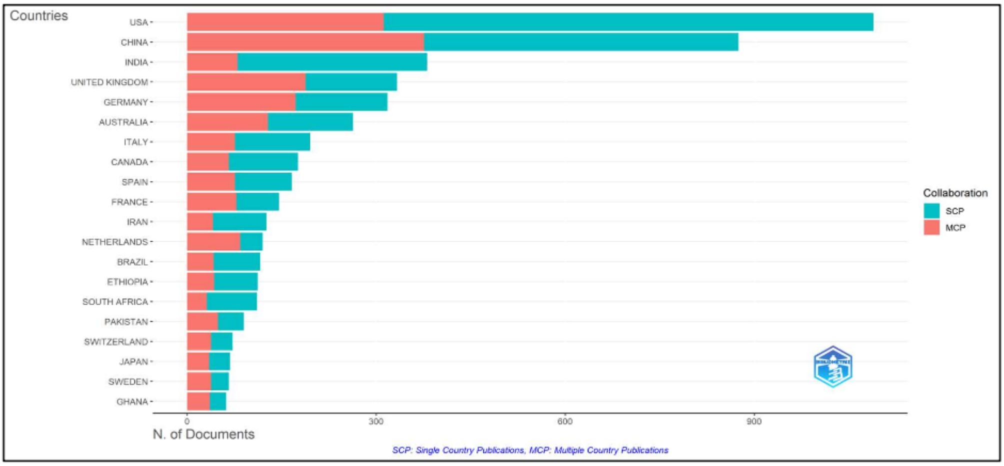

Figure 5: Geographical Affiliation of the Corresponding Author

Table 2: Most Contributed affiliation

Affiliation	**No. of Articles**
Chinese Academy of Science	705
CGIAR	405
University of California System	283
Wageningen University and Research	242
United States Department of Agriculture (USDA)	220
Commonwealth Scientific and Industrial Research Organization (CSIRO)	188
Centre National de La Recherche Scientifique (CNRS)	187
INREA	173
Indian Council of Agricultural Research (ICAR)	166

Participants in the Network of International Collaboration represent several countries that are contributing to research globally in Figure 6. Some of the largest domestic nodes demonstrating participants by name and size include the United States, China, the United Kingdom, Germany, and Australia. Contributions from additional countries can be found on multiple continents, including Canada, India, Japan, Italy, and Brazil. Further, collaborative Connections identified by the edges connecting the network nodes represent each country's collaborative research links. Collaborative connections indicate that research does not occur in a vacuum. For example, the United States has established direct connections with researchers in China, the United Kingdom, Germany, and Australia, indicating that researchers in these countries work together to publish joint papers. Moreover, the thickness of the gray edges connecting the nodes represents the strength or frequency of collaborative partnerships. The strongest connection in the entire network is the link between the United States and China, indicating that the bilateral research relationship between the United States and China is the strongest of any bilateral relationship. The United States also has a significant number of collaborative partnerships with the United Kingdom and Australia, as represented by their thick edges connecting the nodes.

The United States serves as the central actor or 'hub' in this network due to its status as the most prominent node and having the most connections to other nodes compared to any other country. As such, it serves as a key intermediary between the geographical regions that are represented in this network. The United States and China are key regional nodes, and the United Kingdom serves as a secondary regional node for the United States and China. More interestingly, there are three different clusters in this scientific community based on collaboration, and this is visually identifiable through colored links that represent different research domains. The Red Cluster consists primarily of the United States and Australia, with many countries from Asia, including Japan, Korea, and Malaysia. The Blue Cluster consists of many countries from Europe, including the United Kingdom, Germany, Italy, and France, as well as countries such as South Africa and Brazil. This includes China and other countries with varied geographical features, such as Canada, India, Mexico, and Iran. Moreover, it is noticeable that the network is 'centralised yet interconnected'. For instance, the network indicates that the United States is the central 'super hub', yet the density of the connections among the three main clusters indicates that there is no fragmentation. This is evidence of the cohesive nature of the global research community, as indicated by the inter-cluster linkages and not the 'cluster-specific' activities. From the geographical features indicated in the network map, it is evident that there is collaboration among countries. For example, the Blue Cluster indicates collaboration between Europe and the rest of the world, and the Red Cluster indicates collaboration between North America and the Asia-Pacific region. An emerging cluster, which is dominated by China, indicates robust interconnections, which form a 'bridging pattern', connecting diverse geopolitical and institutional research interests, such as those in the Middle East and South Asia. Moreover, most of the nodes are close to one another, which indicates that there is a close relationship between research interests.

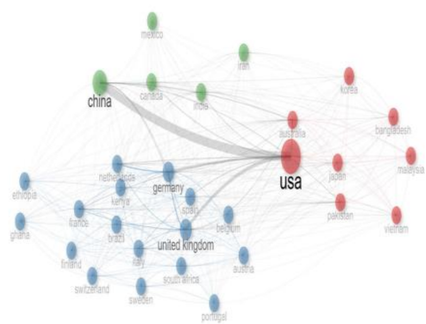

Figure 6: Collaboration Network

3.4 Authorship and Collaboration Patterns

When examining the authors and their number of publications, Muller C has the most articles with 32 publications, followed by Liu Y with 26 and Lobell DB with 25. Li Y and Zhang Y both are reporting the same number of articles (23), while Kumar P and

Schmid E have each contributed 20 articles. Popp A and Zhang L published 18 articles, and Hoogenboom G has published 17 articles. Examining the authors' scholarly output over time reveals a peak in 2014, marked by the highest number of articles (7) attributed to Muller C. and Schmid F. When considering the local impact of authors as measured by the H-index, Muller C. (25) and Lobell DB (24) demonstrate the highest influence (Table 3). Following them are Ewert F and Schmid Eboth with an H-index of 16, and Hasegawa T, Olesen JE, and Poppa, each with an H-index of 15. In terms of individual author impact, Lobell DB has received the highest total citation count (6380) during the period, with Muller C. also receiving significant recognition (4138 total citations). The most widely cited publication about climate impacts on agriculture globally is the article entitled "Climate Impacts on Global Agriculture Emerge Earlier in New Generation of Climate and Crop Models," written by Muller C. in 2021.

Table 3: Most Relevant Authors Bibliometric

Authors	No. of Articles published
Müller C	32
Liu Y	26
Lobell DB	25
Li Y	23
Zhang Y	23
Kumar P	20
Schmid E	20
Popp A	18
Zhang L	18
Hoogenboom G	17

3.5 Keyword and Thematic Analysis

A large number of the keyword occurrences in the entire 6500 publications could likely point towards some of these key themes, or areas of research. For example, the most frequently recognized keyword (1386 occurrences) throughout this dataset was ‘agriculture’, with ‘climate-change’ (1291), ‘impacts’ (1179), and the next group of keywords includes ‘variability’ (722), ‘adaptation’ (681), and ‘temperature’ (619), followed closely by ‘management’ (552) and ‘model’ (552). The nature of the keywords indicates that practical solutions and analytical tools are included in the main topics of study in the field. There are several other noteworthy keywords within the top-ranked keywords of this dataset, for example, ‘yield’ (394) and ‘precipitation’ (378), which show that there has been a great deal of research on these factors related to agriculture, climate, and society's ability to adapt and manage. Similarly, several other keywords such as ‘climate’ (219), ‘risk’ (203), ‘soil’ (192), ‘irrigation’ (175), ‘emissions’ (169), ‘farmers’ (164), ‘wheat’ (163), ‘China’ (158), ‘food’ (153), ‘policy’ (150), ‘maize’ (147), and ‘Africa’ (140) are indicative of some geographical context, crop type, policy considerations, or other environmental factors that have been included in the research. Further, other keywords such as ‘mitigation’ (132) and ‘future’ (131) show that this field is also interested in solutions and a long-term outlook.

As can be seen in the visual representation of Figure 7, the keyword analysis establishes connections and relative prominence amongst various keywords in the source text. A larger circle represents more frequent use of a particular keyword; thus, ‘agriculture’, ‘climate change’, and ‘impacts’ were identified as the most frequently used in the text. Central keywords are grouped by their association with other keywords (related) that have been subdivided into clusters of keywords (colours) that represent commonalities between them. A good example of this is the green cluster surrounding 'climate change', which includes synonyms for climate change such as 'temperature', 'precipitation', and 'drought', and other associations such as 'crops' like maize and wheat. This example illustrates how climate change will affect crop production and the environmental changes associated with climate change. The red cluster around 'agriculture' and 'impacts' encompasses terms such as 'adaptation', 'vulnerability', 'food security', 'farmers', 'risk', 'resilience', and 'strategies', highlighting the socio-economic responses and consequences related to agriculture. The connections between the keywords, represented by lines, indicate the co-occurrence of these terms within the analyzed text, revealing the interconnectedness of these research areas.

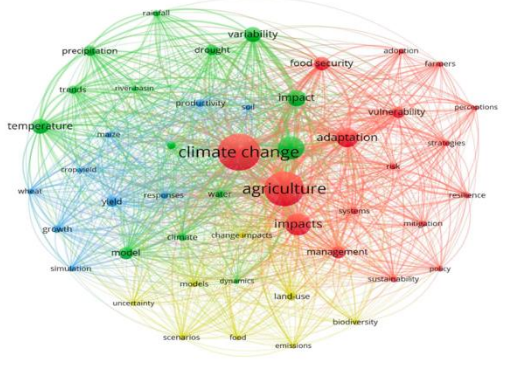

Figure 7: keyword analysis

3.6 Co-occurrence network

The figure 8 shows that the nodes in this network, which include climate change and agriculture, are very prominent and therefore are also frequent. For instance, climate change is associated with several other keywords (e.g., food security) within the dataset. These keywords represent the main subjects of the research and, therefore, provide insight into what the researchers were interested in as they worked on their studies. Another way of looking at this would be that these two keywords are the foundation for all the other keywords. Research shows that other important keywords include variability, impacts, adaptation, and temperature. In addition to showing the dominant themes and major themes in this network, the lines that connect these nodes demonstrate how these themes are interrelated. For example, within this network, the line that connects the two nodes of climate change and management indicates that many studies are related to both management and climate change. Link Strength (Co- occurrence Intensity) The thickness of the lines between items indicates the strength of the connection between them.

Primary Connections, the very thick blue lines between the three items 'climate change' (Climatic Change), 'agriculture' (Agricultural Systems), and 'adaptation' (Adaptation Strategies) show that there is a high level of co-occurrence, suggesting that these three topics define the 'core' of climate change agriculture. Secondary Connections: The thick gray line that connects 'agriculture' (Agricultural Systems) to 'variability' (Variability) provides a strong bridge between the broad climate impact theme on agriculture to technical modeling of weather systems. Colors (Collaboration Theme Clusters) The network is divided into three distinct theme clusters represented by three colors: Blue Cluster (Impact and Adaptation). This is the most prominent theme with respect to the effect of climate change on agricultural production and agriculture in general, with a heavy emphasis on adapting to, managing, and securing food sources. Red Cluster (Climate Variable and Climate Modeling). This theme focuses on the technical/physical components of climate science. Key theme variables associated with this theme are: variability, temperature, rainfall, scenarios, modelling, and generally associated with yield and carbon. Green Cluster (Sociological & Strategic Implementation). This is the smallest of the three themes, highlighting the human and strategic aspect of the research with an emphasis on strategies for mitigation, farmers' perceptions, and the strategies that farmers use when implementing adaptation strategies.

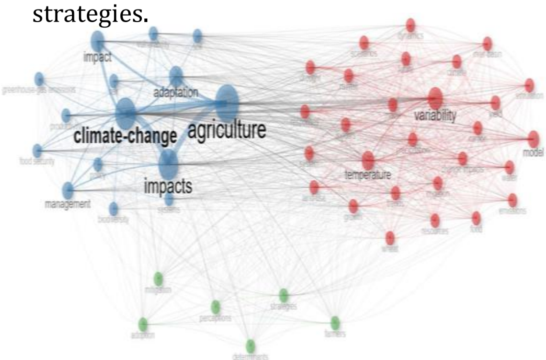

Figure 8: Keyword Co-Occurrence Analysis

3.7 Citation and Co-citation Analysis

The data shows that the mean total citations per article are higher in 2006 at 194.46 (See Figure 9). The average total citations per article began at 60.56 in 2000, and greatly increased to 194.46 in 2006. From that point on, there were some minor fluctuations, but the raw number continues to decline rather consistently until it is just over 0.04 by the year 2024.

Examining the most locally cited sources reveals that Climatic Change leads with 7,904 local citations. The following are P Natl Acad Sci USA (5667), Science (5585), and Global Environmental Change (4,706). When considering the total citations by country, the USA emerges as the most cited with 55,457 citations, followed by China (21,293), the United Kingdom (19,369), Australia (13,723), and Germany (11,825). While the average article citation in the USA is 50.9, Austria demonstrates the highest average article citation at 91.60.

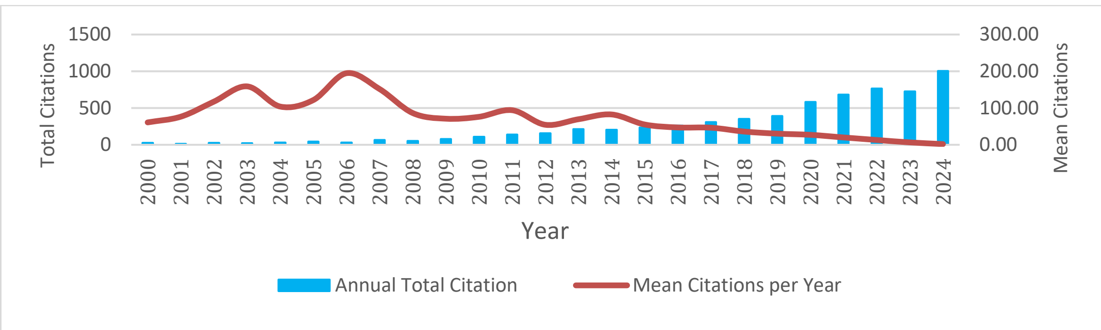

Figure 9: Annual Total Citations and Mean Citation per Year from 2000 to 2024

The evolution of scholarly output and its impact from 2000 to 2024. Initially, in 2000, articles had a Mean Total Citation per Article of 60.56, with 25 articles published and a Mean Total Citation per Article of 2.33. While the number of articles shows a consistent and significant increase, particularly after 2019, over 500, reaching 1004 by 2024.

Mean Total Citation per Article peaked around 2003 (158.60) and 2006 (194.46) before generally declining, plummeting to a mere 1.56 by 2024. Similarly, Mean Total Citation per Article after an initial rise, also shows a general decrease in later years, dropping to 0.78 by 2024. The data point out a trend showing that although there has been a huge increase in the number of articles published, an article's average citation impact per year has dropped considerably over time. This appears to be related to the vast increase in the volume of published work over time and the decreasing number of years a new article will be cited from the date of publication.

The article that has been cited the most globally is 'Adger, 2006, Global Environ Chang', which has received a total of 3704 citations for an average of 185.20 citations per year and has a normalised citation score of 19.05. The article 'Riahi, 2011, Climatic Change', with 2063 total citations and a normalised citation score of 22.02, also indicates a high impact level based on its date of publication. 'Kalnay, 2003, Nature', with 1736 total citations, and 'Lobell, 2007, Environ Res Lett', with 1430 total citations, represent many citations but have lower normalized citation scores than the aforementioned articles. Other noteworthy articles in this research group include 'Challinor, 2014, Nat Clim Change', and 'Ray Dk, 2015, Nat Commun', both of which have significantly high citations and high normalised citation scores, and both of which continue to have an impact based on their relatively recent date of publication. Several of the primary journals from which the majority of articles in this data set are derived, to date, have provided the primary evidence of long-term high-impact brown field research: Global Environmental Change, Climatic Change, Nature, Environmental Research Letters, Nature Climate Change, and PNAS, and they reflect a significant range of high-impact brown field research. The most cited top ten countries and sources are shown in Table 4.

Table 4: Most Cited Countries and Sources from 2000 to 2025

Most Cited Countries			**Most Cited Sources**	
Country	**Total Citation**	**Average Article Citations**	**Sources**	**Citations**
USA	55457	50.90	Climatic Change	7904
China	21293	24.30	Proceedings of National Academy Of Science	5667
UK	19369	58.20	Science	5585
Australia	13723	52.20	Global Environmental Change	4706
Germany	11825	37.20	Nature	4364
Italy	6823	35.00	Science of The Total Environment	4345
India	5818	15.30	Nature Climate Change	4002
Netherlands	5768	48.10	Journal of Hydrology	3960
Austria	5406	91.60	Environment Research Letters	3740
Spain	5070	30.50	Global Change Biology	3724

3.8. Research Gaps and Future Directions

The results of the study show that the United States significantly contributes to the research for the field of climate change and agriculture. Wu et al. (2023) pointed out that as the world's top food commodity producer, the United States boasts the most varied array of funding organisations and offers the greatest volume of research grants. When it comes to research output, the U.S., China, the U.K., Australia, Germany, and India are the leading contributors and the primary drivers of innovation in this field. Historically, the U.S. led research in the initial stages, followed by the U.K, looking at a holistic view. The U.S. holds the position of global leader in climate impact on agriculture research, with the Chinese Academy of Sciences, Wageningen University, and the University of Leeds being the most active research institutions. The results were further implied by showing that the United States and China stand out as the most influential countries (Ajibade et al., 2023; Yang et al., 2023; Sweileh, 2020). Furthermore, Ajibade et al. (2023) have mentioned that the most frequently cited papers in this field were spearheaded by researchers in the United States. The prevailing research trend regarding climate change impacts on crop pests and diseases centers on agricultural production and food safety, alongside the ongoing development of modeling and crop growth studies. Notably, according to Yang et al. (2023), Chinese scholars were highly represented among the top 20 most relevant authors, whereas the first authors of the top 20 most cited papers were from the US.

According to Sweileh (2020), Sustainability has emerged as the dominant journal, and the USA is currently the highest contributor. Additionally, France and the Netherlands saw peak collaboration internationally, while collaborations published by India and China were significantly lower than those of the other countries mentioned. Some of the main thematic areas that were demonstrated through the author keywords from this period include climate change, food security, droughts, adaptation, and agriculture, as well as water scarcity. Other than that, this research shows that impact" and management are also frequent author keywords. Yuan & Sun (2021) selected this research theme because of the increasing recognition of climate change's profound effects on rice production. Analysis of scholarly output indicates that the leading journals in this area, each publishing more than 64 papers, include Science of the Total Environment (with 97 papers, representing 2.872 % of the total), Climatic Change (71 papers, 2.102 %), Agricultural and Forest Meteorology (66 papers, 1.954 %), Global Change Biology (65 papers, 1.925 %), and Sustainability (64 papers, 1.895 %). The geographical areas of interest for this research study will be the People's Republic of China, the United States, India, Australia, and Japan.

There have been big changes in agricultural research over time, especially within the last couple of decades, with much of the recent agricultural research focused on climate change adaptation and using new technology-smart. Previous trends had broader ranges of topics, and the majority of modern research is focused on digital innovations to help with today's agricultural challenges. Li et al. (2024) provided an early analysis of important research topics. In their analysis, important terms commonly used within research were climate change, agriculture, impact, adaptation, and management. Because of this evidence, there is a strong understanding of how closely related climate and agricultural practices are to each other. At different points in time, there are four distinct areas of research that have been identified; however, most of these research areas have ultimately become focused on how agricultural practices can adapt to the changing climate (Kushartadi et al., 2023). More recently, technological advancements have produced new areas of research. Several co-word analyses, including Xu et al. (2024) provided insight into broad research categories, including the themes of: digitalization & sustainable agriculture, smart agriculture & biodiversity conservation, technological applications & agricultural challenge management, and digital intelligence & farmer adoption. The emergence of these clusters signals the increasing awareness of the potential for technology to create agricultural systems that are more resilient and efficient. Further validating this trend are studies analysing the frequency of terms relating to agriculture using algorithms such as Louvain, which identify the dominant areas of agricultural research. For example, Armenta-Medina et al. (2020) identified precision agriculture, smart agriculture, remote sensing, and climate-smart agriculture as the most frequently used terms in agricultural research. The emergence of such terms demonstrates the emergence of a cohesive movement towards innovative and environmentally sustainable approaches to farming. In addition to the macro-trends, there is a growing body of research analysing the micro-level effects of these technologies. An important area of research is understanding how farmers adopt digital intelligence to increase their productivity and how technologies can be used to manage farm production (Xu et al., 2024). From both individual farmer perspectives as well as larger organizational management perspectives, understanding these two forms of research will be critical for effectively implementing smart farming. Escalating research production and growing collaborative efforts across disciplines demonstrate the increasing interest in smart agriculture. Analysing the citation patterns in this rapidly growing sector gives researchers insights into which researchers will have the greatest influence on the field as it continues to evolve.

Technology is drastically changing how we approach precision agriculture, also known as ‘smart farming’. A recent study that utilised bibliometric tools for identifying research areas in modern precision agriculture (Anand et al., 2023) identified several areas with great promise for future research, including greater use of data analytics, drone technology, and Internet of Things (IoT) devices, as well as new techniques for applying precision agriculture concepts. Due to the uncertainty of future impacts of climate change and the complexity of agricultural systems, recent research in agricultural systems involves major interdisciplinary collaboration between agriculture, climate science, environmental studies, and socioeconomics. Furthermore, climate change poses a significant threat to human health and safety as well as the natural environment, both in the short-term and long-term. To meet the challenge of climate change, many researchers utilize computation tools for developing machine learning (ML) based computations to assist in better understanding climate change, developing ways to mitigate the impacts of climate change, and developing adaptation strategies (Ajibade et al., 2023). According to Rejeb et al. (2022), the Internet of Things (IoT) will fundamentally change how farmers use technology and resources, thereby benefiting both owners (farmers/ranchers) and consumers (food producers). The IoT provides real-time data about the health of crops, how much water goes into watering them, and other climate-related factors. Many IoT applications are not easily accessible through other means. Using IoTs in conjunction with other technologies, such as wireless networks, blockchain, Unmanned Aerial Vehicles (UAVs), AI techniques, and big data, will allow farmers to automate their farming activities, maximize their yields, produce higher-quality food, and operate in a sustainable manner. These shifting farming practices have already begun to accept "sustainable" practices. Many IoT solutions will enable decision-making by farmers and ultimately help deliver information to an educated rural community, limiting the use of physical interactions within their operations, enhancing predictive abilities, and lessening chemical pesticide usage, along with improved agri-food traceability. The bibliometric research of Bhuyan (2024) confirms the accuracy of this theory by confirming that the IoT will continue to transform agriculture with the use of data analysis, smart farming, and sensors, resulting in higher agricultural production, sustainability, and efficiency. The author of this research will emphasize the relationship between IoT, big data, machine learning, and sustainable agriculture as a justification for why a transdisciplinary focus is necessary for future research in relation to food security and environmental sustainability. Therefore, the importance of supporting collaborative IoT applications for smart farming must be valued. According to Patil et al. (2023), as well as Rejeb et al. (2022), today's farmers can utilise the Internet of Things (IoT) to better understand their environment, which allows them to make more informed decisions regarding their crop selection and/or the proper use of insecticides and fungicides. The use of drones has also led to revolutionising agriculture, allowing farmers to save a significant amount of money, operate much more efficiently, and be more profitable than before. A bibliometric analysis of the existing literature shows that the following areas of agricultural drones are trending within this field: remote sensing, precision agriculture, deep learning, machine learning, and the Internet of Things. In fact, Luckyardi et al. (2022) found 999 citations when searching for "climate-smart agriculture" on Google Scholar, with 132 being applicable to this body of research. The number of citations for climate-smart agriculture increased between 2017 to 2019 before decreasing in 2020 and then increasing significantly again in 2021. Geospatially studying how coastal communities perceive climate change has produced some interesting outcomes. The U.S. has the most studies, followed to a lesser extent by India and China. The studies typically utilise correlation networks as part of their methodology behind studying social perceptions of climate using methodologies of vegetation and climate combined with data through GIS. The in-depth review of the keywords revealed ten main areas of focus for research: Adaptation, Risk, Community, Local, Impact, Livelihood, Farmer, Household, Strategy, and Variability. Of all the core themes found, the theme 'Adaptation' was the core theme representing the strongest correlations, suggesting its importance across these other themes. This work falls in an interdisciplinary area that combines both social and environmental aspects, suggesting there is plenty of room for future improvement and research to enhance our understanding of the complexities associated with reducing the impacts of climate change. Reducing the impacts of climate change cannot be achieved solely through government policies; therefore, all stakeholders (businesses, members of the public, and other organisations) must incorporate sustainable policies into their practices. As an example of business practices, proper materials, eliminating waste, and producing environmentally safe products are some of the areas that can be evaluated; while for the public, their habits should minimise their environmental impacts. Information and communication technology-based education on climate change can be used as another valuable contribution to solving and understanding climate change (Maharana & Pal, 2023). To effectively solve and overcome different complex challenges posed by climate change's impact on agriculture, future research needs to emphasise the importance of a holistic coupled Earth system approach and the application of the food–energy–water nexus concept. An integrated perspective will allow for the creation of effective, actionable decision-support tools tailored for local and regional scales that will ultimately lead to sustained national agricultural productivity. In addition, current research needs to assess the ability of climate-smart agricultural practices to provide broader contributions toward the goals of reducing global warming (Wu et al., 2023).

4. CONCLUSION

To investigate the literature in the field of climate change and agriculture, a bibliometric analysis of scientific research was conducted using Web of Science (WOS) data based on PRISMA guidelines. It was found that there has been substantial growth in the number of publications pertaining to climate change and agriculture, with accelerating rates of publica-tion beginning around 2014. The United States is the country with the largest number of pub-lications (4,039) and the greatest number of corresponding authors, followed by China (2,781), indicating the US's considerable contribution to the body of research associated with agriculture and climate change. As one of the largest producers of food commodities globally, the US also has the largest number and most diverse types of funding sources and research grants. Muller C, Liu Y, and Lobell DB were identified as the most prolific authors. Frequent keywords in the literature include ‘agriculture’, ‘climate change’, and ‘impacts’. This research is vital for advancing understanding of climate change and fostering sustainable development, offering valuable insights for researchers, policymakers, and practitioners. Future research should embrace a holistic, coupled Earth system approach, incorporating the food-energy-water nexus, to develop effective, localised decision support tools and quantify the mitigation potential of climate- smart agricultural practices to ensure food security. Indeed, this study tackles the research question by demonstrating how the scientific network globally on the nexus between climate change and agriculture has progressed over the period of time from 2000 until 2024. While noting the trend towards an increase in the number of publications, the study findings show how there is a shift in focus towards impact-driven and sus-tainability-based approaches to climate change and agriculture, which focuses on adaptation and resilience. This is further demonstrated by how the study identifies the countries that produce the most scholarly outputs on this topic, highlighting the existence of regional gaps within the field despite its global significance.

However, several methodological limitations associated with the current study are notable. First, bibliometric analysis is conducted based on the WoS database only, which is very comprehensive, but still not all relevant studies may be found here as there could also be some articles available in other databases like Scopus and even regional ones, so there would be potential risk of database bias. Next, the choice of specific keywords used for conducting the search could miss some studies, especially those that were published using other terminologies, which is another limitation. Another aspect to note here is that bibliometric analysis only evaluates characteristics like publication, citation patterns, and keyword co-occurrence, without assessing their validity, context, methodology, and other aspects. Citation-based indicators are also influenced by temporal biases and various disciplinary citation practices, which could distort the analysis as well. Lastly, visualisation with VOSviewer tool requires choosing certain parameters, including thresholds and clustering methods, which could affect network construction. Despite the noted limitations, the current study gives a comprehensive picture of global research trends in the topic under discussion; however, it would be worth considering some recommendations for future research, including combining bibliometric methods with qualitative studies.

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