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Review

Mapping the Landscape of Climate-Smart Agriculture and Food Loss: A Bibliometric and Bibliographic Analysis

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Abstract: Global food security has been significantly affected by climate change; hence, there is a need to come up with lasting and adaptable agricultural practices. The objective of this study is to understand the relationships between climate-smart agriculture (CSA) and food loss management, as these are essential fields that influence sustainable agriculture. By conducting a detailed bibliometric and bibliographic analysis, we have mapped out the research landscape regarding the intersection of CSA and food loss; more importantly, we have concentrated on climate-smart strategies' implementation for the reduction of losses all through the agricultural value chain. Our investigation combined results concerning types of crops that can survive extreme weather conditions like droughts caused by global warming or cold snaps from severe weather events. This work brought out core research directions, clusters, and the regional distribution of scholarly articles, giving an understanding of the present state of CSA and food loss study.

Keywords: climate-smart agriculture; food loss management; sustainable agriculture; climate resilience; food security

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1. Introduction

Climate change presents unprecedented challenges to global food security, necessitating innovative approaches to agricultural practices and food management systems [1]. In this context, the convergence of climate-smart agriculture (CSA) and effective food loss management emerges as an essential domain for sustainable agricultural development [2]. CSA encompasses a range of strategies aimed at enhancing agricultural productivity, resilience, and sustainability in the face of climate variability and change [3]. Simultaneously, addressing food loss throughout the agricultural value chain is imperative for ensuring food security, reducing waste, and maximizing resource efficiency [4]. As the global population, which is projected to reach 9.7 billion by 2050 according to the United Nations, continues to grow, the pressure on food systems intensifies, exacerbating the impacts of climate change on agricultural production and food availability [5]. Climate-related events such as extreme weather events, shifts in temperature and precipitation patterns, and changing pest and disease dynamics pose significant threats to crop yields and livestock productivity [6–8]. Moreover, these challenges are compounded by socio-economic factors, including poverty, limited access to technology and resources, and inadequate infrastructure, which further hinder the resilience of agricultural systems and exacerbate food insecurity [9,10].

Against this backdrop, the integration of CSA principles and practices offers promising solutions to enhance the adaptive capacity of agriculture to climate change while simultaneously addressing food loss and waste [11]. By employing climate-resilient crop varieties, adopting precision farming techniques, optimizing water use efficiency, and promoting sustainable soil management practices, CSA endeavors to mitigate the adverse impacts of climate change on agricultural production while improving productivity, resource use efficiency, and resilience [12,13]. These strategies not only contribute to reducing greenhouse gas emissions and enhancing ecosystem services but also hold potential for minimizing post-harvest losses and improving overall food security [14,15].

The African continent, with its vast agricultural potential, is a poignant example where the impacts of climate change are already being felt, with countries like Ethiopia facing severe droughts that have led to crop failures and food shortages [16]. For instance, in sub-Saharan Africa, where climate variability severely affects crop yields [17], implementing CSA practices such as drought-resistant crops and improved irrigation systems has shown significant promise [18]. Studies have demonstrated that these practices can increase productivity by up to 50%, helping to mitigate the impacts of erratic weather patterns on food security [19,20]. Conversely, in regions like South Asia, food loss during post-harvest stages remains a vital issue [21]. Here, enhancing storage facilities and adopting better logistics can drastically reduce losses, which currently account for up to 40% of total production [22,23].

On the other hand, in the face of climate change challenges, CSA emerges as a beacon of hope. It is not just about mitigating the effects of climate change but also about building resilience and enhancing productivity in agricultural systems [24]. For example, vertical farming in urban locations of developed countries like the United States not only reduces the carbon footprint but also ensures food security by minimizing the impact of seasonality on food production [25]. Similarly, nanotechnology in agriculture is revolutionizing how we approach input efficiency and stress management, as seen in advanced agricultural practices in countries like Germany [26].

However, the effectiveness of CSA is heavily contingent on the ability to manage food losses effectively [27]. Post-harvest losses in developing countries like India, where a significant portion of the produce spoils due to inadequate storage and transportation facilities, present a major hurdle in achieving food security [28]. It is here that the role of CSA becomes even more pronounced, as it integrates practices that not only make agriculture more resilient to climate change but also reduce these post-harvest losses, thereby ensuring that more food reaches the tables that need it [14].

This literature review aims to explore the synergies between CSA and food loss management, synthesizing existing research findings and identifying avenues for future research and innovation. By critically examining the current body of knowledge, this review seeks to provide insights into unexplored areas, innovative approaches, and practical implications for advancing sustainable agriculture and food security in a changing climate. Through a multidisciplinary lens, this review contributes to the ongoing discourse on climate-smart agriculture and offers actionable recommendations for researchers, policymakers, and practitioners striving to build resilient and sustainable food systems globally.

For this study, three research questions are listed below:

1. How do the identified collaborative networks and thematic patterns influence the development and implementation of comprehensive strategies aimed at enhancing agricultural sustainability and food security amidst climate change?
2. What are the key issues and trends emerging now in interdisciplinary research on CSA and food loss?
3. How do the clusters identified in the bibliometric analysis, and the keyword co-occurrence, reflect the evolving approaches from the interdisciplinary standpoint and emerging trends in CSA and food loss research?

This paper now seeks to analyze CSA and food loss as a field. Specifically, this introduction will deal with the significance and the point of departure from which analyzing CSA and food loss begins. The methodology section will use bibliometric and bibliographic analysis, including co-citation of authors' analysis, co-word analysis of keywords, and bibliographic coupling. The results section will present the fruits of the analysis relevant to the research trends of major thematic and geographic areas of major activity. Based on the findings, the conclusion will discuss the implications for new knowledge advancement and directions for future research on CSA and food loss.

2. Literature Review

In a nutshell, sustainable agriculture is providing for the needs of the present generation in terms of food without compromising the ability of future generations to meet these needs, very much in the way that the United Nations has set out its Sustainable Development Goals [29]. In this regard, sustainable agriculture directly contributes to the achievement of SDG 2 with the aim of zero hunger by providing long-term food security through increased productivity and environment conservation [30]. This also supports SDG 13 with the adoption of approaches to reduce the impacts on climate change, which includes GHG emissions reduction and increased sensitivity to climate [31]. Sustainable agriculture further supports SDG 12 in that it promotes efficiency in the use of resources, reduction of loss, and promotion of stable supply chains [32]. The triple bottom line approach to sustainability is what makes the approach to agricultural practices holistic in that the environmental, social, and economic considerations are the same [33]. For instance, vertical farming (VF) is a sustainable innovation that reduces the environmental impact by reducing the carbon footprint connected with lowering land and water use. Socially, VF provides urban employment and better food accessibility [34]. It also helps reduce transport costs and reduces the negative impact based on seasonal variations, making food supply more reliable and resilient [35]. While life cycle analysis indicates that electricity consumption by VF accounts for the majority of the carbon footprint, the increasing use of renewable electricity can offer a low-carbon production method not subject to seasonality, highlighting its potential as a sustainable alternative, especially under changing climate scenarios [36]. Similarly, the introduction of nanotechnology emerges as a novel avenue toward bolstering agricultural sustainability, particularly in optimizing input efficiency and stress management [37]. Moreover, refined modeling methodologies are proposed to attenuate uncertainties in crop yield prognostications amidst climate change dynamics, potentially revolutionizing predictive accuracy [38]. Composting, which is a preferred method to convert biodegradable wastes into nutrient-rich soil conditioners, and biochar-complemented compost show promise as synergic soil amendments to improve soil quality, increase crop production, and remediate contaminated soils. Research on mineral-enhanced biochar and biochar-compost to improve rice yield demonstrates its potential benefits for agricultural sustainability [39]. Advocating for the broader integration of agricultural biodiversity, scholars contend for fortifying productivity and resilience within farming systems, which aligns with circular economy principles [40]. Furthermore, scholars suggest that cassava could play a crucial role in African agriculture's adaptive strategies due to its potential resilience to future climate shifts when compared to another staple crop [41]. The emergence of climate change as a critical threat to global food security necessitates a concerted effort towards mitigation and adaptation strategies. Proactive investments in adaptation are imperative, encompassing the development of climate-resilient germplasm and enhanced management practices [42,43]. Novel approaches such as nanotechnology offer promising avenues for bolstering agricultural sustainability by optimizing input efficiency and stress management [44]. Moreover, the refinement of modeling methodologies aims to attenuate uncertainties in crop yield prognostications amidst changing climate dynamics, thereby enhancing predictive accuracy [45]. These new advances protect crops against the dual menace of drought and floods, the frequency of which increases the adverse impacts of climate change. All of these practices, by allowing crops to be much better off under these two conditions, contribute positively toward the long-term stability and productivity of the agricultural system [46]. Recognizing the vulnerability of smallholder farmers to climate change, tailored interventions are essential to augment their adaptive capacities [47]. Socioeconomic agriculture is intertwined with equity, more so with regard to smallholder farmers, who form the backbone of food production in many regions, for instance, Nigeria [48]. The question of equitable development thus broadly involves ensuring that these farmers have access to resources, knowledge, and technologies in order to implement sustainable practices. Policies should work towards the integration of smallholders and ease the pathway by which they could shift towards sustainable methods without putting undue or inordinate financial and social burdens on them [49]. It contributes not only to livelihood enhancement but also to food security strengthening in communities. This is because cooperative and community-based models contribute to building a collective association among farmers, as noted in the rising trend of adoption of CSA practices among banana farmers in China [50]. These models enhance social sustainability through community resilience, the sharing of knowledge, and collective bargaining power, which better enable smallholder farmers to adopt and sustain environmentally friendly practices. This way, sustainable agriculture will be increasingly achievable for and beneficial to all, leaving no one behind in global sustainability efforts. Furthermore, the integration of agricultural biodiversity is advocated to fortify productivity and resilience within farming systems [51]. Collectively, these endeavors contribute to a nuanced understanding of the intricate interplay between climate change and agricultural systems, elucidating diverse pathways for adaptation and mitigation to safeguard global food security amidst mounting environmental challenges. Additionally, advances in digital technologies in agriculture offer opportunities to enhance ecosystem services delivery and foster sustainable land use practices [52,53]. However, realizing climate-smart agriculture requires a comprehensive understanding of the links between farming practices, adaptation options, and farm performance, underlining the need for standardized indicators and innovative management approaches [54,55]. By addressing these challenges, stakeholders can work towards resilient agricultural systems that mitigate climate risks and ensure food security for future generations. Furthermore, agroforestry systems, CSA practices, adaptation strategies for smallholder farmers, crop residue retention, and the impact of global warming on wheat production are highlighted as integral components of climate-resilient agriculture [56–60]. These diverse approaches underscore the multifaceted nature of climate change adaptation in agriculture and emphasize the need for tailored interventions across different contexts to ensure sustainable food production and security. Additionally, empirical research in Bangladesh investigates the dynamic impacts of agricultural activities on greenhouse gas emissions, highlighting the need for sustainable and climate-smart agriculture policies [61]. Proposing an approach to designing climate-smart production systems, structured in four steps, demonstrates improvements in various performance indicators, indicating the potential of such systems to contribute to agricultural sustainability [62]. Assessing the impact of adopting climate-smart agricultural practices (CAPs) on rice yield in Chinese provinces highlights the positive correlation between CAP adoption and crop yield, with implications for food security [63]. Smart agriculture, incorporating digital technologies, is seen as pivotal in enhancing food security, reducing resource inputs, and increasing farm profitability, although its adoption rate remains low and varies geographically [64]. Meanwhile, a study in Southern Europe maps agricultural areas at risk of climate zone shifts due to climate change, emphasizing the need for resilient agriculture and early action [65]. Finally, the trade-offs and synergies of climate-smart agricultural practices are examined in Western Africa, revealing differences in prioritization between agroecological zones and implications for future CSA action plans in vulnerability hotspots [66].

3. Materials and Methods

The utilization of extensive literature review, coupled with various bibliographic coupling techniques, has emerged as a robust scientific methodology for acquiring comprehensive data and charting new research avenues [67]. This approach is particularly advantageous for analyzing topics that traverse multiple research domains or exhibit interdisciplinary characteristics. Bibliographic coupling proves to be a valuable tool, especially when exploring nascent scientific concepts, aiding in the delineation of methodological boundaries for the subject under investigation [68,69]. CSA and food loss management exemplifies these conditions, encompassing economic, agricultural, and environmental dimensions while still occupying a relatively new and undefined position within the scientific landscape [2].

Database and Search Strategy

In identifying contributors to the scholarly landscape, as they relate to CSA and food loss, we began our full search on Clarivate Analytics Web of Science Core Collection on 29 March 2024. Searches were conducted to retrieve literature on CSA, food loss management, post-harvest losses, food security, sustainable agriculture, and climate adaptation. The search strategy applied was a precise Boolean query: "(Climate-Smart Agricult* OR Climate Resilient Agricult*) AND (Food Loss Manag* OR Post-Harvest Loss OR Food Security) AND (Sustainable Agricult* OR Climate Adaptation)", and it identified an initial corpus of 933 articles.

Inclusion Criteria: Although the screening process was rigorous, it did not limit studies with a time range in an attempt to ensure a wide scope of relevant literature. The inclusion criteria were based on the direct relevance of the articles to the themes mentioned above, excluding those that fell out of our research objective. These were studies on sustainable agriculture, environmental impacts produced by agriculture, and novel techniques for farming, as well as peer-reviewed research articles and articles that contributed empirical data.

Exclusion Criteria: This excluded non-peer-reviewed articles, opinion pieces, research articles not available in English, and research not containing empirical data. It also excluded studies whose main focus was theoretical frameworks that did not use practical data. Sensitivity analysis was performed by excluding studies with high risk of bias.

Data Extraction and Management: Search results were also imported into reference management software to facilitate deduplication. The two reviewers proceeded independently with the relevance assessment, which was conducted from titles and abstracts. Articles judged to be potentially relevant, based on the inclusion criteria, proceeded to the next step—eligibility assessment—that consisted of an independent full-text review of all potentially eligible studies by two reviewers for confirmation of inclusion. Any discrepancies were resolved through discussion or consultation with a third reviewer. Two reviewers independently assessed the risk of bias.

Truncation Method: Truncation involves using the root of a word and an asterisk (*) to retrieve all variations of that word [70]. We further applied truncation to key terms using the asterisk (*), which helped widen our search to root words. For example, "Agricult*" would bring out "Agriculture", "Agricultural", and "Agriculturalists".

Visualization and Analysis: Initial results were tabulated and visually presented using summary tables. Afterwards, qualitative and quantitative data from a large dataset were extracted and analyzed using VOSviewer 1.6.2 software [71]. This software enabled intellectual structure mapping in a given field that helped to identify the emerging trends in research, thematic areas, and geographic distribution of scholarly contributions.

Coupling Bibliometric Process: Bibliographic coupling was used for the analysis of intellectual structure and emerging trends related to themes of CSA and food loss management. This technique involves identifying documents with the same references, hence creating the link between such documents by shared citation. In other words, the more the two documents share references, the more similar the themes are, and more likely the research is clustered under the same thematic area.

VOSviewer Software and Map Creation: This study used VOSviewer, a software tool developed for constructing and visualizing bibliometric networks, to conduct bibliographic coupling analysis. The process starts by importing the entire set of identified articles into the software, which then calculates the strength of bibliographic coupling between any two documents. It then uses this information to create bibliographic maps in which each node is a document, with the distance between nodes being a measure of the bibliographic coupling. Clusters can be formed based on the density of the connections between the nodes, thus showing different thematic areas within the research field.

Visualization and Thematic Analysis: The obtained bibliographic map identified and visualized clusters of closely related research by the cited references. These clusters were further assessed to identify key themes, emerging trends, and literature gaps. The bibliographic coupling maps distinctly and graphically present the intellectual structure of the field, pointing out what links different areas of research and guiding the identification of new avenues of research. Further, assessments of the geographic distribution and temporal trends were made to know how research into CSA and food loss management has evolved over time and across regions.

4. Results and Discussion

This section examines scientific publications on CSA and food loss through bibliometric and bibliographic analysis techniques. By employing bibliometric methods such as co-citation analysis, it uncovers trends, influential authors, and emerging topics while also mapping intellectual connections among publications through bibliographic coupling analysis.

4.1. An Examination of Scientific Publications in the Domain of CSA and Food Loss through Bibliometric and Bibliographic Analysis

The dynamics in the number of relevant publications are depicted in Figure 1. Following this, the bibliometric and bibliographic analysis of scientific publications in the domain of CSA and food loss was undertaken. This analysis involved examining the trends, themes, and patterns evident in the literature, aiming to identify key research areas, influential authors, and emerging topics within the field. By employing bibliometric techniques, such as co-citation analysis and keyword analysis, insights were gained into the structure and evolution of research in CSA and food loss. Additionally, bibliographic coupling was utilized to map the intellectual connections among publications, shedding light on the interdisciplinary nature of CSA and food loss research and its intersections with related fields such as sustainable agriculture, climate adaptation, and food security. The findings of this analysis provide valuable insights for understanding the current state of research in CSA and informing future directions for scholarship in this important area.

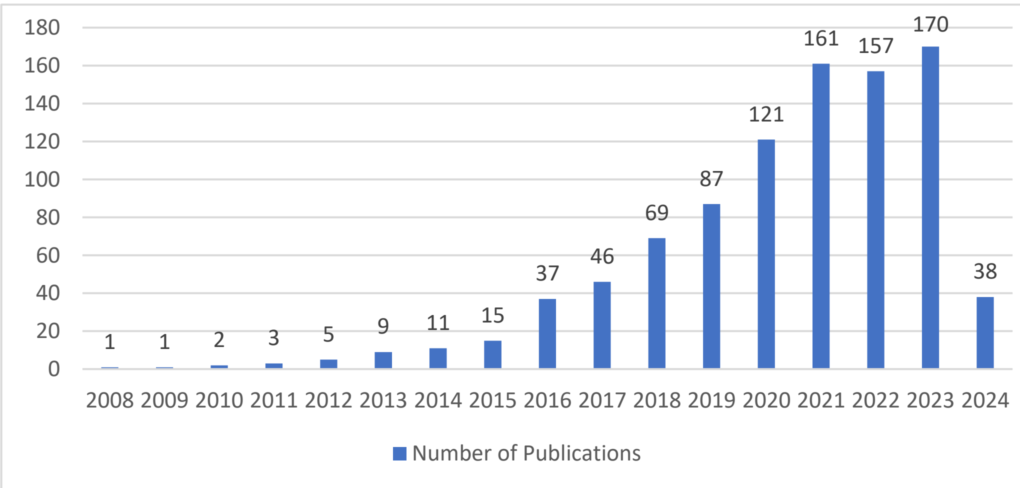

Figure 1. Trend in the number of publications on CSA and food loss over time.

Analyzing the notable spikes in the number of publications related to CSA during specific years, such as the substantial increase from 2015 to 2020, several factors may contribute to this trend. Firstly, the years following 2014 witnessed a surge in scientific interest, potentially driven by the release of the FAO memorandum on the promotion of CSA, which provided a framework for research and implementation efforts in this domain [2,72,73]. Additionally, advancements in technology and methodologies for studying agriculture and climate change may have facilitated increased research output during this period. Moreover, growing global awareness of climate change impacts on agricultural systems and food security likely prompted researchers to explore innovative solutions such as CSA, further fueling publication activity [74]. Furthermore, funding initiatives and international collaborations aimed at addressing climate-related challenges in agriculture may have incentivized researchers to contribute to the growing body of CSA literature [75,76]. Overall, the observed fluctuations in publication numbers likely reflect the evolving landscape of scientific inquiry, with varying degrees of emphasis on CSA research in response to changing environmental, social, and policy contexts.

The analysis is initiated by delving into individual-level scrutiny of papers within the CSA and food loss domain. To discern which scientific publications have wielded the most influence in propelling research in this field, an exhaustive review of citation metrics was conducted. Specifically, the 20 most cited papers pertaining to CSA were identified and compiled, organized based on their average citations per year. This methodology enables pinpointing seminal works that have garnered substantial attention and recognition within the scientific community over time. Scrutinizing the impact and trajectory of these highly cited papers offers valuable insights into the predominant themes, methodologies, and findings that have shaped research in the CSA domain. Table 1 presents the selected papers, providing valuable insights into the seminal contributions driving scholarly discourse and innovation in CSA.

Table 1. Top 20 most cited papers.

Authors	Source Title	Times Cited	Average per Year
Hanjra and Qureshi [77]	Food Policy	854	61
Lowry et al. [37]	Nature Nanotechnology	503	101
Liu et al. [60]	Nature Climate Change	354	44
Harvey et al. [78]	Philosophical Transactions of The Royal Society B-Biological Sciences	349	35
Frison et al. [40]	Sustainability	325	25
Cairns et al. [79]	Food Security	287	26
Asseng et al. [80]	Global Change Biology	271	54
Jarvis et al. [41]	Tropical Plant Biology	239	20
Wang et al. [38]	Nature Plants	227	32
Navarro-Racines et al. [42]	Scientific Data	212	53
Arslan et al. [43]	Agriculture Ecosystems and Environment	201	20
Purakayastha et al. [45]	Chemosphere	197	39
Wang et al. [44]	Nature Nanotechnology	197	99
Simelton et al. [47]	Environmental Science and Policy	194	13
Makate et al. [81]	Springerplus	190	24
Sultan et al. [82]	Environmental Research Letters	189	17
Gurung et al. [51]	PLoS One	142	14
Makate et al. [83]	Journal Of Environmental Management	141	28
Huang et al. [84]	Agriculture Ecosystems and Environment	134	22
Lajoie-O'Malley et al. [52]	Ecosystem Services	132	33

Table 1 offers a revealing snapshot of the top 20 most cited papers in CSA and food loss research. Remarkably, these papers collectively amassed thousands of citations, with the highest achieving over 800 citations, underscoring their profound impact on the scholarly community. Delving into the data, it is intriguing to note that 3 out of the 20 highly cited papers emerged in 2019, suggesting a particularly prolific year for groundbreaking research in the CSA domain. Furthermore, the average citations per year provide valuable insights into the enduring relevance of these publications, with some maintaining an impressive average of over 50 citations annually. This underscores not only the immediate impact but also the sustained influence of these seminal works over time. Additionally, the diverse array of journals represented in the list underscores the interdisciplinary nature of CSA research, spanning disciplines from environmental science to agriculture.

Across various papers spanning from 2009 to 2022, a consistent theme emerges, highlighting the urgent need to address the challenges facing global agriculture amidst climate change. By analyzing the common theme, it was identified that many scholars advocate for proactive measures to bolster food security and resilience in the face of shifting climatic conditions. They stress the importance of investing in climate-resilient agricultural practices, technological innovation, and adaptive strategies to achieve sustainable food production. Notably, emerging theoretical frameworks underscore the critical role of interdisciplinary research, innovative technologies like nanotechnology, and the preservation of agricultural biodiversity in cultivating resilient agricultural systems [42,80]. Moreover, the dominant literature emphasizes the necessity of tailored adaptation strategies to mitigate the disproportionate impacts of climate change on vulnerable smallholder farmers while also emphasizing the need for more accurate climate impact assessments and crop yield projections to guide evidence-based decision-making in agriculture [37,79]. The prevailing theoretical sprouts stress the significance of innovative approaches such as conservation farming practices, biochar application, nanopesticides, and crop diversification in enhancing soil quality, boosting crop yields, and building resilience against climate variability [43,79]. Additionally, prominent research underscores the importance of precise climate data and modeling techniques for evaluating the potential impacts of climate change on agriculture and biodiversity [79,81]. Collectively, these findings emphasize the necessity of interdisciplinary research, access to agricultural extension services, and tailored interventions to assist farmers in adopting climate-smart agricultural practices, ultimately contributing to global food security and sustainable agricultural productivity. The current research offers actionable insights and policy recommendations, underscores the urgency of addressing climate change impacts on agriculture, and highlights the interconnectedness of food systems and ecosystem services. Therefore, the adoption of climate-resilient agricultural practices, alongside technological advancements and informed decision-making, emerges as an essential strategy for enhancing adaptive capacity and ensuring food security amid a changing climate [44,45].

A bibliographic coupling procedure was undertaken to explore the relationships between scientific publications in the field of CSA and food loss, with the findings illustrated in Figure 2. This analysis offers insights into the interrelations and common themes prevalent across the CSA literature. To ensure a focused examination, documents appearing fewer than 50 times were excluded, leaving a total of 90 documents with frequencies of 50 or more.

Among all the articles included, six clusters were identified, and the highest number of citations was observed for Hanjra (2010) [77] with 854 citations, followed by Lowry (2019) [37] with 503 citations, and Liu (2016) [60] with 354 citations. Notably, despite having fewer citations, some articles exhibit substantial total link strength, indicating strong connections with other publications. For instance, Arslan (2014) [43] has 201 citations but a total link strength of 51, suggesting significant co-citation with other articles. Conversely, while some articles have high citation counts, their total link strength may be relatively lower, indicating less interconnectedness within the literature. This underscores the importance of considering both citation counts and total link strength to assess the influence and interconnectedness of scientific publications in the field of CSA and food loss research. Additionally, articles such as Lowry (2019) [37] and Defries (2016) [85] demonstrate relatively high citation counts despite their minimal total link strength, suggesting potential for further exploration of their impact and connections within the literature. The analysis of highly cited articles reveals several noteworthy trends and insights. While some articles, like Hanjra and Qureshi (2010) [77] in "Food Policy", exhibit exceptionally high citation counts, indicating their significant impact and influence over time, others, such as Lowry et al. (2019) [37] in "Nature Nanotechnology", demonstrate high average citations per year, suggesting sustained relevance and ongoing scholarly interest. Interestingly, diverse publication outlets are represented among the top-cited articles, ranging from prestigious journals like "Nature Climate Change" and "Nature Plants" to specialized publications like "Tropical Plant Biology" and "Chemosphere". Furthermore, the topics covered by these articles span a wide spectrum, from climate change and agricultural sustainability to nanotechnology and ecosystem services, reflecting the interdisciplinary nature of research in the CSA and food loss domain. These findings underscore the multifaceted nature of scholarly contributions to the field and highlight the importance of examining both citation counts and publication outlets to gain a comprehensive understanding of research impact and dissemination in this area.

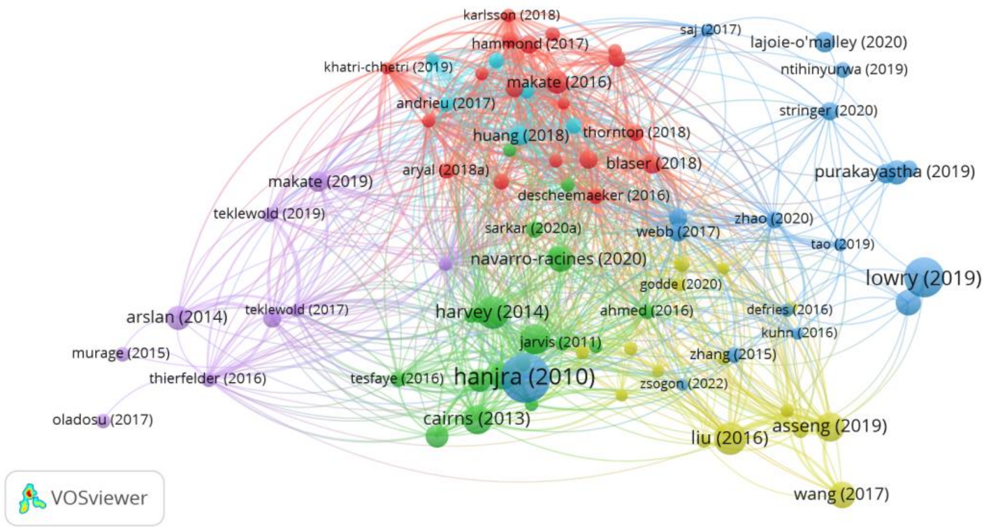

Figure 2. Bibliographic coupling analysis of publications on CSA and food loss from 2009 to 2022.

4.2. Analysis of the Most Prolific Institutions in the Field of CSA and Food Loss through Bibliometric and Bibliographic Methods

The analysis of the most prolific institutions in the field of CSA and food loss through bibliometric and bibliographic methods is imperative for comprehensive scholarly understanding. This examination facilitates the identification of leading contributors and research trends within these domains, thereby informing strategic collaborations and resource allocation [39]. Moreover, it serves to gauge the efficacy of research investments and supports evidence-based decision-making by funding agencies and policymakers [86]. Furthermore, by delineating influential institutions, this analysis aids in fostering scholarly networks and mentorship opportunities for emerging researchers [87]. In essence, such scrutiny plays a pivotal role in advancing scholarly discourse and addressing pertinent challenges in agriculture, food security, and sustainability.

Table 2 provides a comprehensive analysis of institutions contributing to research in CSA and food loss, revealing notable patterns and insights. To ensure a thorough representation of global research within our study, we implemented specific criteria for inclusion. When a publication involves authors from various countries, we designate the credit to the nation with the largest author contribution. However, in instances where no single country holds a majority and the authors are uniformly distributed across multiple nationalities, we include each of these publications in our analysis. This approach allows us to accurately reflect the collaborative and international nature of the research efforts in the field. The International Center for Tropical Agriculture (CIAT) emerges as the most prolific institution with 40 documents and 1552 citations, indicating significant influence in the field, closely followed by the International Maize and Wheat Improvement Center (CIMMYT). Despite variations in document counts, institutions like the University of Leeds and the International Crops Research Institute for the Semi-Arid-Tropics (ICRISAT) demonstrate substantial citation impact, emphasizing the importance of quality research output. The presence of renowned international research centers like the Consultative Group on International Agricultural Research (CGIAR) alongside prestigious universities such as Wageningen University highlights the collaborative and interdisciplinary nature of CSA research. The geographic diversity of these institutions underscores the global significance of CSA research in addressing agricultural challenges worldwide. However, the unequal distribution of publications among institutions suggests the need for broader engagement and collaboration to advance CSA research comprehensively.

Table 2. Institutional contributions to CSA and food loss research.

Institution	Documents	Citations	% of Total Publications
The International Center for Tropical Agriculture	40	1552	4.3%
International Maize and Wheat Improvement Center	39	1208	4.2%
Wageningen University	34	939	3.6%
ICRISAT	33	1008	3.5%
University of Leeds	29	1217	3.1%
Wageningen University and Research	26	411	2.8%
Addis Ababa University	18	151	1.9%
Kwame Nkrumah University of Science and Technology	18	179	1.9%
CGIAR Research Program on Climate Change, Agriculture and Food Security	17	543	1.8%
Chinese Academy of Sciences	17	222	1.8%
Université de Montpellier	17	308	1.8%
International Center for Tropical Agriculture	16	802	1.7%
University of Agriculture Faisalabad	16	123	1.7%
International Livestock Research Institute	15	898	1.6%
The International Center for Agricultural Research in the Dry Areas	15	137	1.6%
Total	350	9698	37.5%

In exploring the collaborative landscape within CSA and food loss research, the analysis reveals the presence of three distinct clusters, as shown in Figure 3, each indicative of unique institutional collaborations and knowledge exchange dynamics. Among these clusters, the green cluster, anchored by the International Center for Tropical Agriculture (CIAT), emerges as a central hub of scholarly endeavors, boasting 40 documents and a remarkable total link strength of 14,295. This cluster not only underscores CIAT's pivotal role but also signifies a robust network of collaborations and knowledge exchange, indicative of CIAT's proactive engagement with diverse stakeholders in tackling agricultural challenges. Similarly, the red cluster, centered around Addis Ababa University, and the blue cluster, spearheaded by the International Maize and Wheat Improvement Center (CIMMYT), showcase notable collaborative efforts, with 18 and 39 documents respectively. These clusters elucidate the intricate web of partnerships and shared expertise driving innovative research in CSA and food loss mitigation. Further analysis reveals CIAT's dominance in the field, contributing 4.3% of total publications with 1552 citations, a testament to its significant impact and influence. CIMMYT follows closely with 4.2% and 1208 citations, highlighting its pivotal role in advancing agricultural technologies and practices. The presence of multiple institutions within each cluster not only underscores the interdisciplinary nature of CSA and food loss research but also emphasizes the importance of collaborative approaches in addressing multifaceted agricultural challenges. This clustering analysis offers valuable insights into the collaborative dynamics shaping the scholarly landscape, paving the way for enhanced partnerships and knowledge dissemination to drive sustainable agricultural innovation in the face of global challenges.

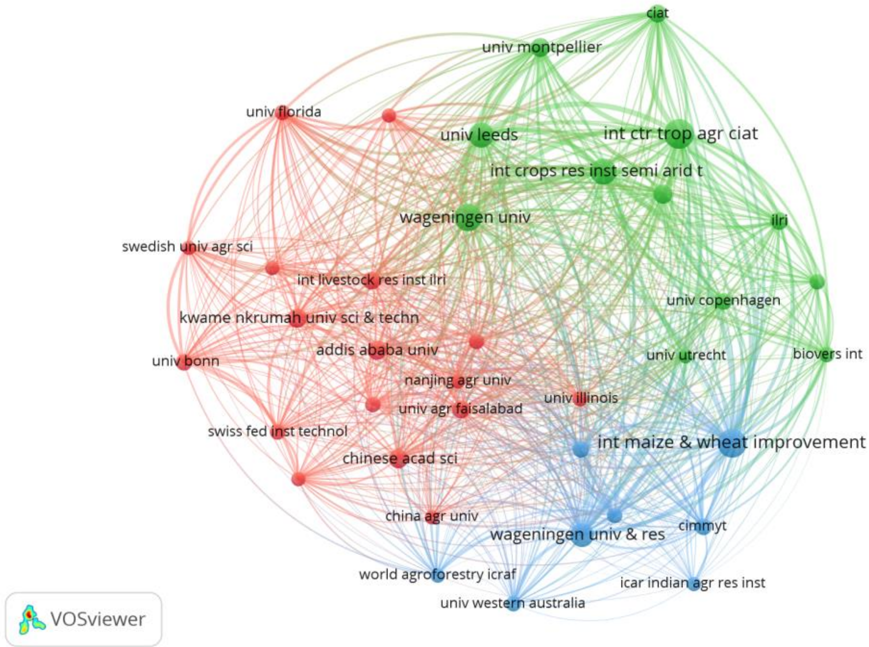

Figure 3. Bibliographic coupling analysis of the leading institutions in the CSA and food loss domain.

In general, all three clusters address paramount challenges such as food insecurity, malnutrition, climate change, and environmental degradation through collaborative research, partnerships, and training. The presence of multiple institutions within each cluster underscores the interdisciplinary nature of CSA and food loss research. It also emphasizes the importance of collaborative approaches in addressing the multifaceted challenges faced by the agricultural sector. By working together, these institutions facilitate the exchange of knowledge and expertise, leading to innovative research and solutions that can be applied globally.

4.3. Analysis of Publications in the CSA and Food Loss Domain Using Bibliometric and Bibliographic Methods

A comprehensive bibliometric and bibliographic analysis was undertaken to discern the primary journals disseminating knowledge pertaining to both CSA and food loss domains. This examination aimed to identify key journal publications contributing to the understanding of CSA and food loss issues. Journals were meticulously selected based on the frequency of articles related to CSA and food loss, as depicted in Table 3, shedding light on the scholarly outlets actively engaged in publishing research on these critical topics. This analysis offers valuable insights into the dissemination landscape of CSA and food loss literature, highlighting the key platforms shaping scholarly discourse in these domains.

Table 3 highlights the pivotal role of select journals in driving scholarly discourse within the CSA and food loss domain. Notably, journals like Frontiers in Sustainable Food Systems and Sustainability emerge as frontrunners, both in terms of publication volume and impact, boasting respectable IF scores and H5-index values. Interestingly, while journals such as Climate and Development and Environment Development and Sustainability have lower publication volumes, their robust IF and H5-index values suggest their potential as emerging influential outlets in the field. Moreover, the inclusion of diverse journals like Agriculture-Basel and Regional Environmental Change underscores the multidisciplinary nature of research in CSA and food loss, hinting at the need for interdisciplinary collaboration and knowledge exchange across various domains. Looking ahead, researchers could leverage the insights from this analysis to strategically target high-impact journals aligned with their research focus, thereby maximizing the dissemination and impact of their findings within the academic community.

Table 3. Journal metrics in the CSA and food loss domain.

Source	Documents	% of Total Publications	IF 2022	H5-Index
Frontiers in Sustainable Food Systems	56	6.00%	4.7	62
Sustainability	48	5.14%	3.9	185
Agricultural Systems	39	4.18%	6.6	77
Agriculture-Basel	18	1.93%	3.6	52
Global Food Security-Agriculture Policy Economics and Environment	17	1.82%	8.9	73
Food Security	16	1.71%	6.7	53
Agronomy-Basel	13	1.39%	3.7	67
Climate and Development	13	1.39%	4.3	48
Environment Development and Sustainability	11	1.18%	4.9	73
PLoS ONE	11	1.18%	3.7	212
Regional Environmental Change	11	1.18%	4.2	56
Field Crops Research	10	1.07%	5.8	69
Heliyon	10	1.07%	4.0	105
International Journal of Agricultural Sustainability	10	1.07%	3.4	31
Land Use Policy	10	1.07%	7.1	1.3
Total	**293**	**31.40%**		

The outcomes derived from the bibliographic coupling analysis, which delves into the interconnections among journals disseminating articles in the CSA domain, are visually depicted in Figure 4. It is essential to emphasize that a criterion was established wherein journals had to feature a minimum of five articles within the CSA and food loss domain to be considered for inclusion in this analysis. This threshold ensures that only journals actively contributing to the scholarly discourse on CSA are accounted for, thereby providing a comprehensive overview of the bibliographic landscape within this field [88]. While each cluster has its unique focus, they are interlinked by the overarching goal of promoting sustainable agriculture and addressing food loss. The differences in the clusters' interconnectivity and thematic scope reflect the diverse approaches and perspectives that contribute to the comprehensive understanding and advancement of the field. The bibliographic coupling analysis of journals unveils fascinating insights into the scholarly landscape. Beyond merely identifying clusters, the analysis delves deeper into the interconnectedness and knowledge exchange dynamics among journals. Notably, certain journals emerge as central nodes within the network, playing pivotal roles in connecting different thematic areas and facilitating interdisciplinary dialogue and collaboration. These journals likely serve as primary platforms for disseminating cutting-edge research and fostering innovation in sustainable agriculture and food systems. Moreover, the analysis reveals emerging trends and focal points of research, providing researchers and policymakers with valuable intelligence to anticipate and address pressing challenges in CSA and food loss mitigation. By discerning the network structure of scholarly communication, the analysis offers a roadmap for optimizing resource allocation, fostering strategic partnerships, and enhancing the dissemination of knowledge to accelerate progress towards sustainable agricultural development and food security.

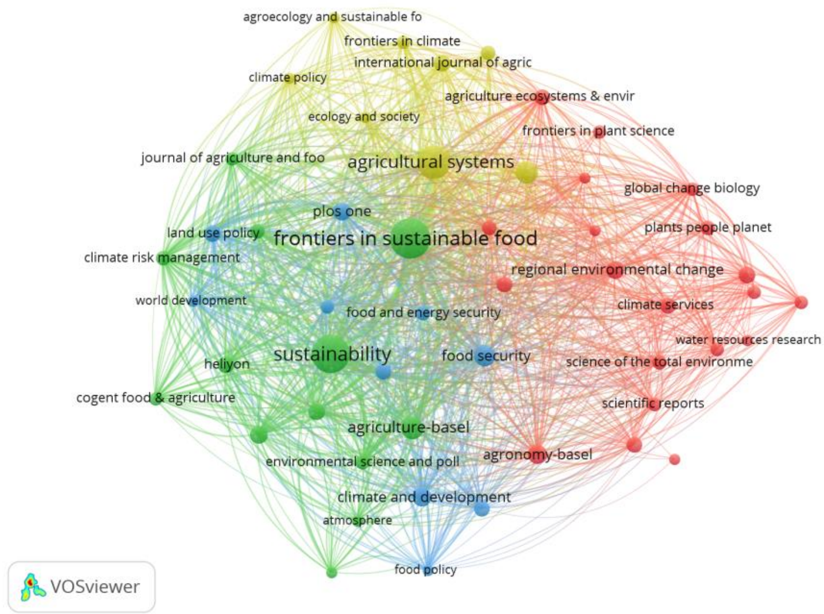

Figure 4. Co-citation analysis of journals in the domain of CSA and food loss.

The co-citation analysis conducted revealed four distinct clusters within the domain of CSA and food loss journals, each characterized by specific thematic foci and interconnections. The green cluster, centralized around Frontiers in Sustainable Food Systems, emerged as the most prominent, featuring a considerable total link strength of 6323 and comprising 56 documents. This cluster signifies a strong emphasis on sustainability within the scholarly discourse on CSA, reflecting the increasing importance placed on environmentally conscious agricultural practices. On the other hand, the red cluster, anchored by Agronomy-Basel, shines a light on specialized research endeavors within the domain. While it exhibited a lower total link strength of 1640, indicative of a niche thematic scope, this cluster showcases a focused and in-depth exploration of specific topics in agriculture. Despite comprising 18 documents, the cluster embodies a rich tapestry of scholarly discourse, offering valuable insights and contributions to the field. This concentration of research expertise underscores Agronomy-Basel's commitment to advancing knowledge and innovation in agriculture, positioning it as a vital contributor to the scholarly landscape. Conversely, the yellow cluster, centered around Agricultural Systems, demonstrated robust interconnections with a total link strength of 5599, indicative of a cohesive network of journals contributing to broader discussions on agricultural systems and practices. Lastly, the blue cluster, centered around Food Security, underscored the important intersection between food security and CSA, with a total link strength of 2405 and 16 documents. This cluster highlights the pressing need to address food insecurity through sustainable agricultural interventions, emphasizing the interdisciplinary nature of research within the CSA and food loss domain. By focusing on key terms related to food security and policy, the blue cluster highlights the multidimensional nature of the challenge and the diverse approaches needed for effective intervention. Through interdisciplinary research published in these journals in the blue cluster, the cluster emphasizes the importance of sustainable agricultural practices in ensuring food security for present and future generations.

4.4. Analysis of the Most Productive Countries in the Domain of CSA and Food Loss through Bibliometric and Bibliographic Methods

To gain deeper insights into the global landscape of research on CSA and food loss, a meticulous examination of the top 10 most productive countries in this domain was undertaken and shown in Table 4. This analysis is important for several reasons. Firstly, it offers valuable insights into the geographic distribution of scientific contributions, highlighting regions where research efforts are concentrated and those where further attention may be warranted. Understanding the regional dynamics of research activity can aid in identifying potential gaps in knowledge and areas requiring additional focus or support. Additionally, by examining the prominence of certain countries in CSA and food loss research, policymakers, funding agencies, and stakeholders can better allocate resources and prioritize collaborative initiatives to address pressing challenges in agriculture and food security on a global scale. Therefore, this analysis serves as a foundational step towards fostering international collaboration and advancing collective efforts to tackle complex issues at the intersection of agriculture, sustainability, and food systems [89,90].

Table 4. Top 10 countries/regions in CSA and food loss publications.

Country/Region	Documents	% of Total Publications
USA	61	6.54%
India	52	5.57%
Ethiopia	19	2.04%
Germany	18	1.93%
People's Republic of China	18	1.93%
South Africa	17	1.82%
England	13	1.39%
Canada	12	1.29%
Kenya	12	1.29%
Australia	11	1.18%
Total	**233**	**24.97%**

The distribution of publications across the top 10 countries/regions reflects not only research output but also disparities in economic development and agricultural infrastructure. Developed countries such as the United States, Germany, and Canada demonstrate high publication numbers, indicating their robust research ecosystems and substantial investments in agricultural innovation [91]. These nations often possess advanced technologies and well-established academic institutions, enabling extensive research on CSA and food loss. Conversely, developing countries, for instance, India, China, and South Africa exhibit notable research contributions, indicative of their growing agricultural sectors and efforts to address food security challenges [92]. Developing and least-developed countries are disproportionately affected by climate change, exacerbating existing food security challenges [93,94]. Regions like the Sahel are particularly vulnerable, experiencing heightened occurrences of droughts, floods, and rapid population growth [95–97]. These environmental stressors necessitate more intensive and productive agricultural practices to sustain growing populations [98]. However, the adverse impacts of climate change impede these efforts, posing significant threats to agricultural productivity and food security [99]. Consequently, these nations have intensified research efforts on CSA as a strategic response to mitigate the repercussions of climate change on agricultural systems [100,101]. This focus on CSA reflects a broader recognition of the need for innovative solutions to enhance agricultural resilience, adaptability, and sustainability in the face of evolving climatic conditions [102]. Despite facing significant developmental challenges, these countries prioritize agricultural research as a means to enhance food security, alleviate poverty, and foster economic growth [103]. The presence of England and Australia among the top contributors reflects the research strengths of these countries within the broader context of global agricultural development. While England's contributions may stem from its historical leadership in agricultural research and innovation [104]. Australia's focus on addressing environmental sustainability and climate change impacts on agriculture drives its research agenda [105,106]. Overall, the distribution of publications across developed, developing, and underdeveloped countries highlights the multifaceted nature of CSA and food loss research, necessitating collaborative efforts and knowledge sharing to address these challenges comprehensively on a global scale.

The analysis revealed eight distinct clusters in the geography of scientific interest in the CSA and food loss domain, as shown in Figure 5. Notably, the red cluster, centered around the USA, emerged as the most prominent, with 61 documents and a total link strength of 3013. This suggests a significant concentration of research activity in the USA within this domain. The green cluster, centered around Ethiopia, also exhibited considerable strength, with 19 documents and a total link strength of 2215. This could be attributed to Ethiopia's unique agricultural landscape and its focus on addressing food security challenges through CSA initiatives [107]. Similarly, the yellow cluster, centered around India, showcased a high level of engagement, with 52 documents and a total link strength of 1689, reflecting India's status as a major agricultural powerhouse and its growing emphasis on sustainable agricultural practices [108]. Other clusters, such as those centered around South Africa, Germany, and China, also demonstrated notable contributions to the field, reflecting the diverse global landscape of CSA and food loss research. Possible factors contributing to these clusters may include governmental initiatives, research funding, academic institutions, and agricultural policies tailored to address specific challenges and opportunities within each country's context [109]. Additionally, collaborations between countries and international organizations may have influenced the distribution of research activity across different regions. Overall, this analysis sheds light on the global distribution of scientific interest in CSA and food loss, highlighting the varied contributions and collaborative networks shaping research efforts in this critical domain.

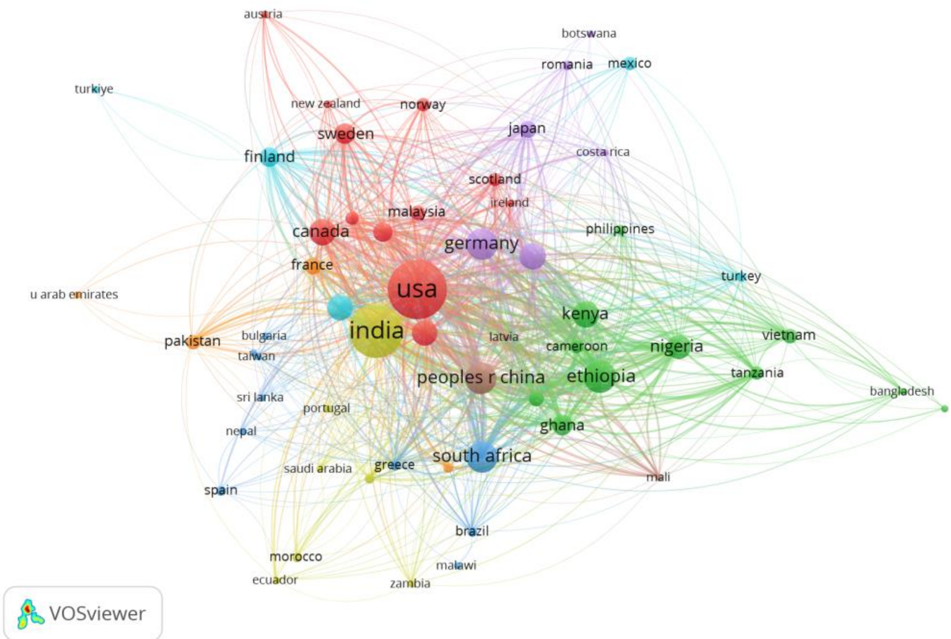

Figure 5. Top countries in CSA and food loss productivity.

4.5. Keyword Co-Occurrence Analysis in CSA and Food Loss

Conducting keyword co-occurrence analysis in the domain of CSA and food loss is important for gaining a comprehensive understanding of prevailing research streams and themes within this field. By examining the simultaneous appearance of keywords across publications, researchers can identify common patterns, emerging trends, and interconnected topics [110]. This analysis enables the delineation of prominent research areas, facilitating the identification of gaps in existing literature and guiding future research directions. Moreover, understanding keyword co-occurrence patterns allows researchers to uncover underlying relationships [111] between different aspects of CSA and food loss, thus contributing to the development of more effective strategies for addressing agricultural sustainability and food security challenges.

The keyword co-occurrence analysis, as shown in Figure 6, revealed four distinct clusters within the CSA and food loss domain. The blue cluster, focused on food security, demonstrates a strong emphasis on addressing issues related to ensuring access to food. The yellow cluster, centered around adaptation, highlights the significance of strategies to mitigate the impacts of climate change on agricultural systems. The red cluster, revolving around CSA, underscores the growing interest in CSA as a solution to enhance resilience and sustainability in food production. Lastly, the green cluster, centered on climate change, signifies the interconnectedness between climate variability and its effects on agricultural practices and food systems. These clusters likely emerged due to the growing recognition of the intricate interplay between climate dynamics, agricultural practices, and food security concerns [112]. As researchers increasingly understand the multifaceted nature of these challenges, there has been a concerted effort to explore comprehensive solutions that integrate climate adaptation strategies, sustainable agricultural practices, and food security initiatives. This recognition has fueled collaborative research endeavors aimed at addressing the complex interactions between climate change and agriculture, leading to the formation of distinct clusters focused on key thematic areas within the CSA and food loss domain [57,113].

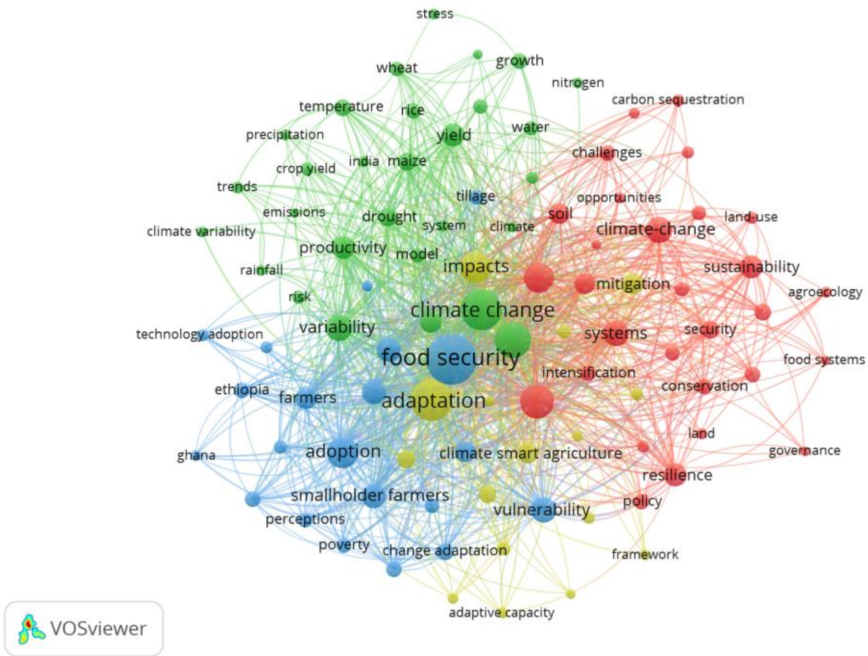

Figure 6. Keyword co-occurrence in CSA and food loss.

The keyword co-occurrence analysis in the CSA and food loss domain reveals intricate connections and thematic concentrations within the scholarly literature. The presence of distinct clusters highlights the diverse yet interconnected nature of research within this field, offering insights into prevailing priorities and emerging trends. For instance, the prominence of terms related to climate change adaptation and mitigation across multiple clusters underscores the urgent need to address the impacts of climate variability on agricultural systems. Additionally, the regional focus evident in certain clusters, such as the blue cluster's emphasis on smallholder farmers in Ethiopia and Ghana, suggests targeted efforts to address food security challenges in specific geographical contexts. Furthermore, the prevalence of terms like "resilience" and "sustainability" underscores a growing recognition of the importance of holistic and integrated approaches to CSA, emphasizing the need for policy interventions and sustainable land management practices. Overall, these findings provide valuable insights into the interconnectedness of research themes and priorities within the CSA and food loss domain, informing efforts to develop comprehensive strategies for building resilient and sustainable food systems in the face of global challenges. The analysis reveals significant trends and commonalities across the four identified clusters within the literature on CSA and food loss, emphasizing a strong focus on agricultural sustainability, resilience, and food security. These clusters demonstrate interconnectedness, with overlapping keywords reflecting complex relationships between different aspects of CSA and food loss. For instance, while the blue cluster emphasizes food security, the yellow cluster highlights adaptation strategies to climate change. This indicates an urgent need for comprehensive solutions integrating climate adaptation measures, sustainable agricultural practices, and food security initiatives to address challenges facing agricultural sustainability. The emphasis on food security in the blue cluster and adaptation strategies to climate change in the yellow cluster suggests an important intersection between food security and climate resilience in agricultural sustainability. This juxtaposition highlights the interdependence between ensuring access to food and mitigating the adverse impacts of climate variability on agricultural systems. The co-occurrence of keywords across these clusters underscores the need for integrated solutions that address both food security challenges and climate-induced vulnerabilities in agriculture. Consequently, there is a pressing need for comprehensive approaches that encompass climate adaptation measures, sustainable agricultural practices, and food security initiatives to address the multifaceted challenges facing agricultural sustainability effectively. This integration is vital for developing resilient agricultural systems capable of withstanding the impacts of climate change while ensuring food security for vulnerable populations. Moreover, the analysis furthermore reveals emerging trends, such as the growing recognition of climate change's impact on agriculture and the emphasis on adaptive capacity building. This underscores a shift towards proactive approaches to address interactions between climatic factors, agricultural practices, and food security outcomes.

5. Conclusions

In conclusion, the study delved into the bibliometric and bibliographic analysis of publications in the domain of CSA and food loss. The results of this study highlight the importance of CSA strategies such as climate-resilient crop varieties, precision agriculture, and sustainable soil management. These measures together mitigate the impacts of climate change on agriculture. Furthermore, the significant increase in the number of relevant publications in the 5-year period from 2015 to 2020 reflects a growing recognition of the urgency of addressing these challenges. This is likely driven by FAO's promotion of CSA and technological advances in the agricultural industry. Through meticulous examination, three central research questions were addressed:

i. Implications of Collaborative Networks and Thematic Patterns: Thematic analysis reveals the importance of interdisciplinary collaboration and knowledge exchange in enhancing agricultural sustainability and food security amidst climate change. Collaborative networks identified within the research landscape serve as vital platforms for sharing best practices, facilitating technology transfer, and fostering partnerships to address complex challenges in agriculture. One of the prominent thematic patterns to emerge is the emphasis on climate change adaptation. As the adverse effects of climate change become increasingly apparent, there is a pressing need for agricultural practices that can withstand and adapt to these changes. This includes the development of drought-resistant crop varieties, the implementation of water-saving irrigation techniques, and the adoption of farming methods that increase soil carbon sequestration. Sustainable agricultural practices are another key theme that has surfaced. These practices are not just about maintaining the health of the environment; they are also crucial for the long-term viability of the agricultural sector. By promoting biodiversity, reducing chemical inputs, and encouraging agroecological approaches, sustainable farming can enhance the resilience of the food system, provide livelihoods for farmers, and contribute to the overall health of the ecosystem. Food security is inextricably linked to both climate change adaptation and sustainable agricultural practices. The thematic patterns that have emerged from our analysis highlight the need for a holistic approach to address the interconnected challenges of food production, environmental sustainability, and socio-economic development. This holistic approach is essential for designing and implementing targeted interventions and policy frameworks that can effectively promote sustainable agricultural practices, enhance the resilience of the food system, and ensure food security for vulnerable populations.

ii. Prevailing Themes and Emerging Trends: Themes such as climate change adaptation, sustainable agricultural practices, and CSA systems intensification emerge as focal points of interdisciplinary inquiry. These themes reflect the interconnectedness between climate dynamics, agricultural practices, and food security concerns, highlighting the need for comprehensive solutions. Emerging trends, such as the integration of innovative technologies, policy frameworks, and community-based approaches, underscore the evolving nature of research in this domain. Interdisciplinary research plays a crucial role in bridging gaps between disciplines, fostering collaboration, and generating comprehensive solutions to address the complex challenges facing agriculture.

iii. Insights from Bibliometric and Keyword Co-occurrence Analyses: The bibliometric analysis provided insights into the geographic distribution of research output, the prominence of certain journals and institutions, and the collaborative networks shaping the field. Meanwhile, the keyword co-occurrence analysis revealed clusters of related terms, highlighting the interconnectedness of topics such as food security, climate change adaptation, CSA practices, and agricultural sustainability. These analyses shed light on the evolving interdisciplinary approaches and emerging trends in CSA and food loss research, guiding future research directions and policy interventions.

First, future research should take interdisciplinary collaboration into consideration, as this method can bring experts from agronomy, environmental science, economics, and social science together, thus fostering innovative solutions for sustainable agriculture. Second, incorporating regional and context-specific analysis can provide a nuanced understanding of local challenges and opportunities, as this allows CSA practices to be tailored to meet regional demands. Third, with the rapid advancement of technologies, future studies should look into how emerging technologies like remote sensing and AI-driven analytics can enhance the effectiveness of CSA initiatives. Additionally, longitudinal studies can study the long-term CSA practice's impact on agricultural productivity and climate resilience. The effectiveness of educating farmers to facilitate the adoption of climate-resilient techniques should also be further studied.

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