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Agro-meteorological services in the era of climate change: a bibliometric review of research trends, knowledge gaps, and global collaboration

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Introduction: Agro-meteorological services are crucial for mitigating climate variability's impact on agriculture and enhancing food security. Despite their importance, the global research landscape in this field remains underexplored. This study examines the evolution of agro meteorological research from 2010 to 2024, focusing on trends, contributors, and regional developments.

Methods: A bibliometric analysis was conducted using the Dimensions database, with visualizations created via VOSviewer. The study analyzed publication trends, key institutions, authors, journals, and subject clusters. Statistical correlations assessed collaboration and institutional impact.

Results: The results revealed that publications increased steadily, peaking in 2020 (r = 0.92, p < 0.01), reflecting emphasis on sustainability and climate adaptation. Collaborative publications correlated strongly with institutional impact (r = 0.75, p < 0.01), led by Wageningen University and the University of Chinese Academy of Sciences. Sustainability and The Science of the Total Environment were key journals. Sub- Saharan Africa and South Asia showed significant research growth (r = 0.85, p < 0.01).

Discussion: The results highlight the field's global, interdisciplinary scope and rising contributions from developing regions. However, capacity gaps and limited integration of indigenous knowledge persist. Inclusive partnerships and capacity building are essential to strengthen agro meteorological services and address climate challenges effectively.

KEYWORDS

agro-meteorological services, climate change adaptation, global research collaboration, bibliometric analysis, climate resilience

Introduction

Agro-meteorological services have become indispensable in addressing the escalating challenges posed by climate variability and its profound impact on agriculture. Global temperatures are rising, and weather patterns are becoming more erratic. These changes put agricultural systems under increasing pressure. They must adapt while also meeting the growing food demand of an expanding population (Allan et al., 2023; El Bilali et al., 2020). Climate-induced changes worsen existing vulnerabilities. This is especially true in regions where agriculture is central to livelihoods and economies (Emediegwu et al., 2022). As a result, agro-meteorological services have emerged as a critical tool, providing actionable climate and

weather information that supports informed decision-making, enhances productivity, and builds resilience within agricultural systems (Food and Agriculture Organization of the United Nations, 2022; Khatibu et al., 2022).

Over the past decade, there has been a concerted global shift toward integrating agro-meteorological tools into agricultural practices to address the intertwined challenges of climate change, food insecurity, and environmental degradation. As such, by combining meteorological data with agricultural applications, agro-meteorological services deliver valuable insights such as seasonal forecasts, drought risk assessments, and pest outbreak warnings (Attri and Mohapatra, 2021; Kumar, 2020). These tools empower farmers to optimize planting schedules, irrigation practices, and pest management strategies, thereby fostering sustainable agriculture and contributing to the broader goals of climate resilience and environmental conservation (World Meteorological Organization, 2021; Cegnar et al., 2023). This integration aligns closely with global efforts, such as the United Nations Sustainable Development Goals (SDGs), specifically SDG 2 (Zero Hunger) and SDG 13 (Climate Action), underlining the role of agro-meteorology in achieving sustainable development (United Nations, 2019). Technological advancements have significantly driven the evolution of agro-meteorological services, with innovations in remote sensing, Geographic Information Systems (GIS), and big data analytics improving their precision, accessibility, and scalability (Carter and Oroy, 2024; Pan et al., 2022). These technologies have enabled the development of highly accurate weather forecasts, real-time monitoring systems, and region-specific climate advisory services, which are essential for diverse agricultural systems globally (Wellstead et al., 2024).

Despite the remarkable progress, significant challenges persist in ensuring equitable access to agro-meteorological services and addressing disparities in their adoption and implementation (Singh et al., 2018; Partey et al., 2018; Wyche and Steinfield, 2016). While some regions, particularly in developed nations, have made significant strides in integrating these services, others—especially in developing countries—face systemic barriers, including limited financial resources, inadequate infrastructure, and the absence of localized and culturally appropriate solutions (Paparrizos et al., 2024; Canton, 2021). Additionally, gender disparities further hinder access, with female farmers often excluded due to structural inequalities in education and resource availability (Diouf et al., 2019; Gumucio et al., 2020).

Existing studies have explored different aspects of agro-meteorological services. These include their ability to reduce climate risks (Buontempo and Hewitt, 2018), boost agricultural productivity (Mwalupaso et al., 2019), and improve food security (McKune et al., 2018). However, the research landscape remains fragmented, with a significant focus on case-specific applications and limited consolidation of broader knowledge frameworks. This lack of comprehensive analysis emphasizes the need for systematic evaluations that identify thematic trends, research gaps, and collaboration patterns to inform future investigations and policy initiatives.

This study employs bibliometric methods to systematically analyze the evolution of knowledge, research trends, and collaborative networks in agro-meteorological services research. Bibliometric analysis offers a robust and quantitative framework for examining global research outputs, identifying key contributors, and mapping thematic areas within the field. Using data from the Dimensions database and visualization through VOSviewer software, this study aims to: (i) analyze temporal trends in agro-meteorological research publications, (ii) map thematic clusters and knowledge domains, (iii) identify major contributors, including influential authors, institutions, and journals, and (iv) highlight emerging research trends and gaps to guide future research and practice. Through this analysis, the study offers valuable insights into the intellectual structure of agro-meteorological services research, identifying gaps and opportunities for innovation. By addressing existing challenges and fostering collaboration, this work contributes to advancing the role of agro-meteorological services in promoting sustainable agriculture, growing challenges of, and achieving global food security in an era of intensifying climate challenges.

Methodology

This study uses bibliometric analysis to thoroughly evaluate the evolution of knowledge and emerging trends in agro-meteorological services research. Bibliometric analysis is a quantitative methodology that assesses academic literature through mathematical and statistical techniques, providing an objective overview of a certain domain (He et al., 2019; Li and Chen, 2016). This method utilises citation data and creates scientific knowledge maps to visually depict the evolution, interaction, and structural linkages within the study topic. Bibliometric procedures reduce subjective bias, ensuring trustworthy and replicable results, while clarifying research patterns and intellectual foundations.

Research data were obtained from the Dimensions database, a comprehensive multidisciplinary repository that offers access to a wide array of scholarly outputs, including journal articles, conference proceedings, and patents. The Dimensions database was chosen for its extensive coverage and capacity to encompass cross-disciplinary research pertinent to agro-meteorological services. The search query included keywords like "agro-meteorology," "climate information services," "climate services" and "agricultural meteorology" to guarantee the acquisition of pertinent material. To ensure the relevance and quality of the studies included in this bibliometric review, we established specific inclusion and exclusion criteria. Inclusion criteria were as follows: studies had to be peer-reviewed journal articles and reviews published between 2010 and 2024, focusing on agro-meteorological services, climate information services, or agricultural meteorology. Additionally, studies needed to be written in English and directly address the impact of climate variability on agriculture, with an emphasis on empirical data or substantial contributions to the field. Exclusion criteria were applied to eliminate studies that did not meet these standards. Specifically, we excluded studies that were not peer-reviewed, such as books, conference proceedings, or theses, as well as papers published outside the specified timeframe. We also removed duplicates, studies not written in English, and those that did not focus on agro-meteorological services or the impacts of climate variability on agriculture. Furthermore, studies that lacked empirical data or did not align with the study's scope were excluded. These criteria ensured that our review was based on high-quality, relevant research, resulting in a final dataset of 1,499 articles for analysis.

Subsequent to the application of these criteria and the elimination of duplicates and irrelevant entries, 1,499 articles were finalized for analysis. Figure 1 demonstrates that the process of identifying publications and selecting articles adhered to the requirements set forth by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). An analysis of published scholarly articles and technical reports on practices agro-meteorology globally.

The bibliometric data were analyzed utilising VOSviewer, a prevalent tool for creating and visualising bibliometric networks.

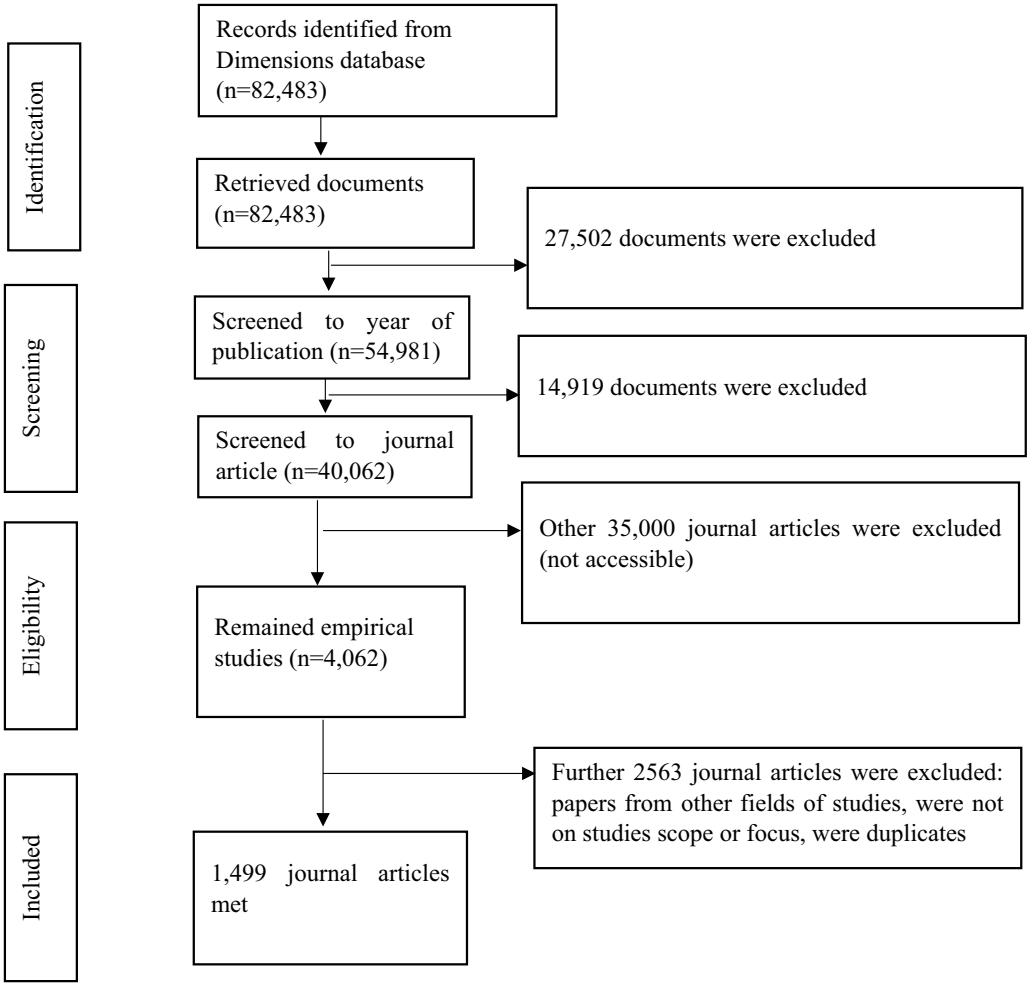

FIGURE 1
The bibliometric procedure, as seen in the PRISMA flow diagram.

VOSviewer possesses the ability to map co-authorship networks, co-citation links, keyword co-occurrences, and institutional collaborations. These analyses offered significant insights into the intellectual framework and research dynamics of agro-meteorological services. Co-authorship analysis discovered prominent writers and collaboration networks, co-citation analysis uncovered seminal works and thematic clusters, and keyword co-occurrence analysis emphasized research hotspots and developing trends. Furthermore, collaborations at both institutional and national levels were delineated to demonstrate worldwide contributions to the discipline.

The methodological workflow started with data collection, during which pertinent papers were obtained through advanced search functionalities in the Dimensions database. Metadata including titles, abstracts, keywords, authors, institutions, and references was extracted for analysis. A data preprocessing procedure was subsequently performed to eliminate duplicates and irrelevant records, hence ensuring data accuracy and consistency. The purified dataset was subsequently loaded into VOSviewer for visualization and analysis, facilitating the discovery of knowledge clusters, thematic patterns, and research gaps. The findings were analyzed to reveal the progression of agro-meteorological services research and its correspondence with global concerns like food security and climate resilience. This methodological approach provides a strong framework for comprehending the intellectual landscape of agro-meteorological services research.

Results

Trends in publication and expansion of agro-meteorological services research

The trajectory of research publications in agro-meteorological services from 2010 to 2024 exhibits a steady upward trend, reflecting the growing importance of this field in addressing climate-related agricultural challenges (Figure 2). In the early phase (2010–2013), research engagement was relatively limited, with fewer than 50 publications per year, indicating the nascent stage of the discipline. However, between 2014 and 2018, the volume of publications increased significantly, reaching approximately 150 by the end of this period. This growth suggests heightened interest and investment, likely driven by advancements in meteorological data collection and the increasing global focus on climate adaptation in agriculture.

A notable surge in research output occurred between 2019 and 2020, culminating in a peak of over 171 publications in 2020. This

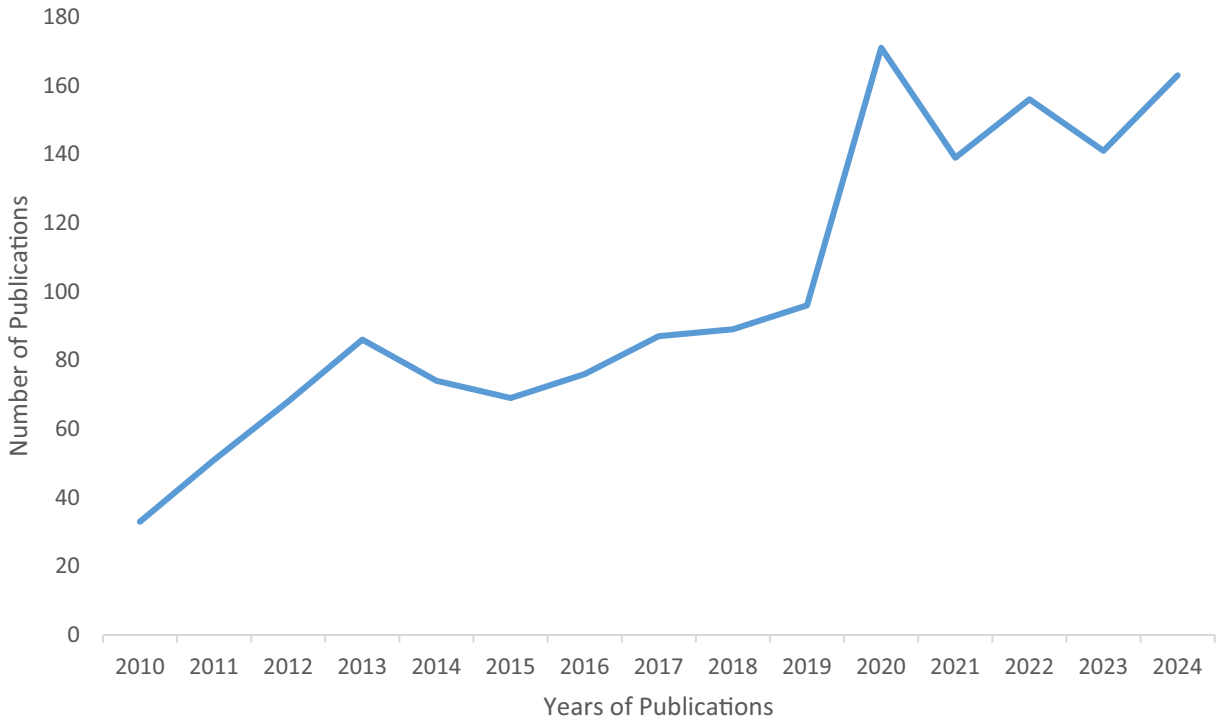

FIGURE 2
Publication trends and growth in agro-meteorological services research over time.

TABLE 1 Publication trends and correlations.

Time period	Publication growth	Correlation (*r*)	*p*-value
2010–2013	Low (≤ 50 papers/year)		
2014–2018	Moderate (≈ 150 papers/year)		
2019–2020	Peak (171 + papers)	0.92	< 0.01
2021–2024	Stabilized (100 + papers/year)		

sharp rise aligns with heightened global awareness of climate change impacts and the increasing integration of agro-meteorological tools into agricultural decision-making processes. The study observes a strong positive correlation between time and publication output ($r = 0.92$, $p < 0.01$), particularly from 2010 to 2020, underscoring the expanding recognition of agro-meteorological services in climate resilience strategies (Table 1).

Following the peak in 2020 (Figure 2), research output stabilized between 2021 and 2024, consistently exceeding 100 publications per year. This stabilization suggests that while research expansion has slowed, agro-meteorological services continue to receive sustained academic attention. The observed trends underscore the growing recognition of these services as essential tools for enhancing agricultural resilience and mitigating climate-related risks.

Principal thematic areas and knowledge domains contributing to the discipline

Figure 3 offers a clear depiction of the interrelated knowledge domains within agro-meteorological services research as an indication of the integration of climate, agriculture, ecology, and scientific inquiry as fundamental elements of the discipline. The network map shows term co-occurrence, highlighting key themes and knowledge domains in agro-meteorological services research. The primary node "Climate change" is the most frequent and influential term. This indicates its central role in the field.It is intricately linked with other terms, highlighting its extensive significance across several research subjects. Three separate clusters can be found surrounding "climate change," each reflecting a thematic focus. The blue cluster highlights farmer-centric themes, featuring keywords like "farmer," "adaptation," "community," and "perception." This cluster represents research on farmer adaptation strategies, community-level responses to climate variability, and the influence of perception on addressing climate challenges.

The green cluster emphasises environmental variables encompassing terms such as "temperature," "rainfall," "precipitation," "forest," and "species." This thematic domain investigates the ecological ramifications of climate change, the influence of environmental factors on agricultural systems, and the interplay between ecosystems and agricultural productivity. Simultaneously, the red cluster emphasizes research-centric keywords such as "research," "climate," "challenge,"

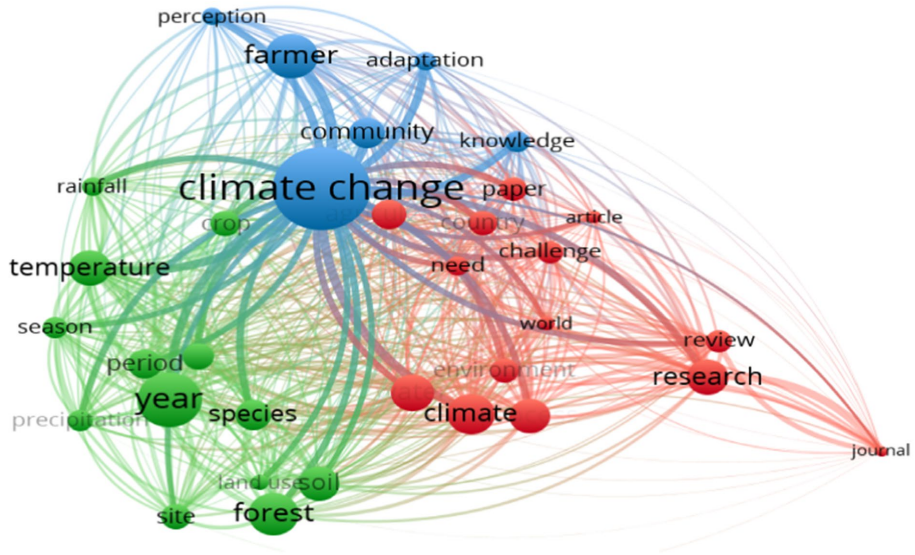

FIGURE 3
Keyword co-occurrence network in agro-meteorological services research.

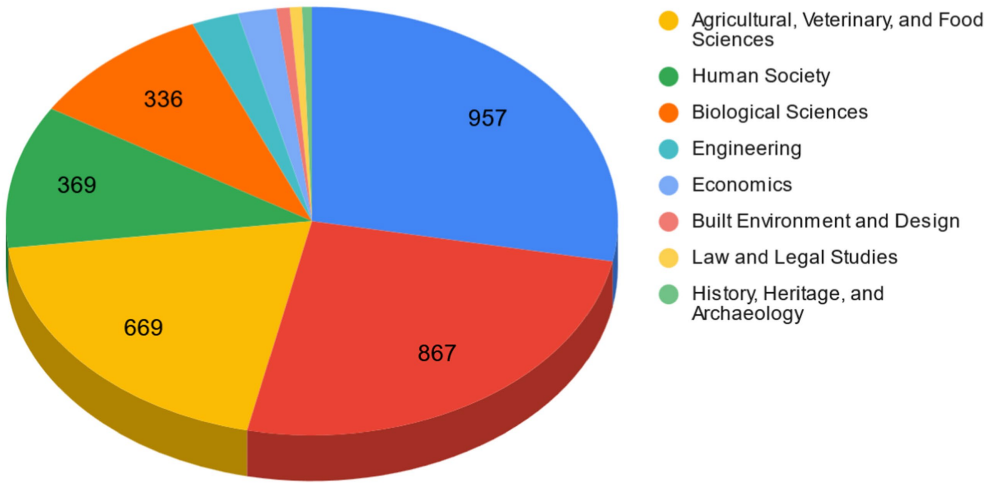

FIGURE 4
Distribution of publications across research fields in agro-meteorological services.

and "journal" as indication of an emphasis on theoretical discourse, meta-analyses, and critical assessments of the research landscape in agro-meteorological services. The map illustrates significant correlations between "climate change" and terms such as "farmer," "adaptation," "temperature," and "forest," which signify comprehensive research on the effects of climate change on agricultural practices, ecological systems, and farmer resilience. Furthermore, concepts like "knowledge," "community," and "research" underscore the significance of knowledge transmission, community involvement, and the progression of scientific comprehension in this domain. Temporal aspects, indicated by terms such as "year," "period," and "season," suggest research examining seasonal and long-term climatic effects on agriculture.

Principal domains of study

The dissemination of research publications concerning agro-meteorological services across several academic fields shows the multidisciplinary character of this topic as shown in Figure 4. Environmental Sciences ranks first with 957 papers on the significance of environmental elements including climate change, ecosystems, and resource management in agro-meteorology. Earth Sciences has 867 papers as an indication of a significant emphasis on geophysical processes, climate modeling, and weather systems that support agro-meteorological research. The Agricultural, Veterinary, and Food Sciences sector has produced 669 articles which demonstrate the practical applications of agro-meteorological services in enhancing

agricultural production, food security, and animal husbandry. The social and biological dimensions are notable, with Human Society producing 369 publications and Biological Sciences yielding 336. These topics emphasize the significance of farmer adaptability, community involvement, and the effects of climate variability on agricultural species and ecosystems.

Other fields, like Engineering (85 papers) and Economics (69 publications), emphasize the technical and economic dimensions of agro-meteorological services, encompassing the creation of robust infrastructure and cost–benefit evaluations of climate interventions. Minor contributions from disciplines like Built Environment and Design (24 publications), Law and Legal Studies (22 publications), and History, Heritage, and Archaeology (18 publications) indicate specialized research interests, including policy frameworks, historical climate trends, and cultural effects of agricultural practices. This distribution illustrates the extensive influence of agro-meteorology, encompassing environmental, agricultural, social, technological, and economic aspects to tackle intricate issues associated with climate change and agriculture. The varied contributions demonstrate the collaborative endeavor necessary to create effective, sustainable, and inclusive agro-meteorological solutions.

Preeminent authors, institutions, and journals influencing research in agro-meteorological services

Figure 5 highlights the highly collaborative and interconnected nature of agro-meteorological research, with contributions led primarily by developed nations. These countries not only drive research advancements but also foster significant collaborations with climate-vulnerable regions to address the intertwined challenges of climate variation and agricultural productivity. Such global cooperation is essential for advancing agro-meteorological services and promoting climate-resilient agricultural systems worldwide.

The country collaboration network map illustrates the global reach of agro-meteorological research and underscores the importance of international partnerships. The United States and the United Kingdom emerged as leading contributors, with substantial research output and a central role in facilitating regional collaborations. Both nations maintain strong research ties with both developed and developing countries, reinforcing their leadership in advancing agro-meteorology on a global scale.

A well-connected cluster is also evident across Europe, comprising France, Italy, Germany, Sweden, and Spain. These countries actively collaborate, reflecting Europe's collective commitment to addressing agricultural and climate challenges. Moreover, European nations extend their research partnerships to Africa and Asia, promoting climate-resilient agricultural systems through cooperative projects and knowledge-sharing initiatives.

In Africa, countries such as Ethiopia, Kenya, and Tanzania have established robust research partnerships with Western nations, particularly the United States, the United Kingdom, and various European countries. This underscores Africa's vulnerability to climate alteration and the increasing reliance on agro-meteorological services to enhance agricultural resilience. Many of these collaborations focus on developing localized strategies to address climatic variability and ensure food security.

Similarly, Asian nations including India, Bangladesh, and Indonesia are major contributors to agro-meteorological research. Their prominence in the research network highlights the heavy dependence of these countries on agriculture and the urgent need for climate adaptation solutions. Over the past five years, research output from institutions in Sub-Saharan Africa and South Asia has shown significant growth ($r = 0.85$, $p < 0.01$) (Table 2), indicating their increasing role in agro-meteorological research and deeper integration into the global research network.

Additionally, emerging contributors such as Mexico, South Korea, and Saudi Arabia reflect a rising global interest in agro-meteorological research, driven by growing climate-related agricultural challenges in

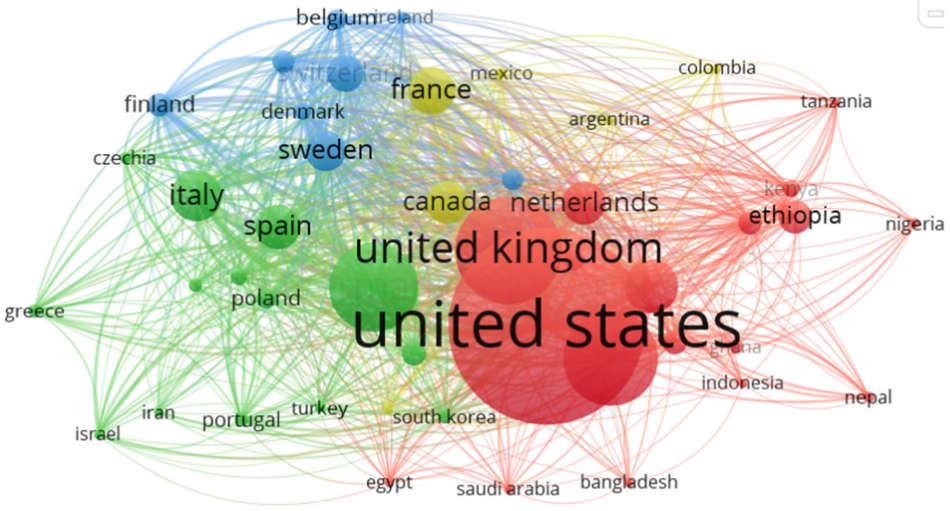

FIGURE 5
Country collaboration network in agro-meteorological services research.

TABLE 2 Research output growth in Sub-Saharan Africa and South Asia.

Region	Growth in research output (2019–2024)	Correlation (*r*)	*p*-value
Sub-Saharan Africa	Significant growth	0.85	< 0.01
South Asia	Significant growth	0.85	< 0.01

TABLE 3 Key contributors in agro-meteorological services research based on publications.

Name	Organization	Country	Publications	Citations	Citation mean
Derek S. Arnid	National Centers for Environmental Information	United States	11	1,462	132.91
Jessica Blunden	National Centers for Environmental Information	United States	9	1,110	123.33
Philippe Ciais	Laboratoire des Sciences du Climat et de l'Environnement	France	8	1,148	143.5
Robert A. Marchant	University of York	United Kingdom	8	385	48.13
Christopher M. Gough	Virginia Commonwealth University	United States	7	542	77.43
Matthew P. Peters	US Forest Service	United States	7	659	94.14
P. Danielle Shannon	Michigan Technological University	United States	6	208	34.67
Wulf Amelung	University of Bonn	Germany	6	131	21.83
Louis R. Iverson	US Forest Service	United States	6	625	104.17
Kristie L. Ebi	University of Washington	United States	6	985	164.17

these regions. The collaboration network highlights strong transcontinental partnerships, particularly between industrialized and developing nations, underscoring the collective effort to enhance adaptive capacity through scientific advancements.

Ten leading authors in the discipline

The examination of significant contributors to agro-meteorological services research, as detailed in Table 3, underscores a cohort of prominent academics and institutions that have markedly propelled the discipline forward. Derek S. Arnid from the National Centres for Environmental Information in the United States is the foremost author in publications, having authored 11 works that collectively garnered 1,462 citations, resulting in a notable average citation score of 132.91. His contributions highpoint the pivotal role of the United States in agro-meteorological research, especially via institutions like the National Centres for Environmental Information.

Likewise, Jessica Blunden, also affiliated with the same school, has 9 publications and a notable mean citation score of 123.33. Prominent researchers with the highest mean citation scores are Kristie L. Ebi from the University of Washington, United States, who attained an impressive 164.17 citations per publication across 6 papers, and Philippe Ciais from Laboratoire des Sciences du Climat et de l'Environnement, France, with a mean of 143.5 citations from 8 publications. These scores stress the impact of their work, signifying that their research has substantially contributed to the scientific community, especially at the nexus of climate science and agro-meteorology.

The United States leads in contributions, with scholars including Christopher M. Gough (Virginia Commonwealth University), Matthew P. Peters (US Forest Service), and Louis R. Iverson (US Forest Service) providing significant input. These individuals embody a variety of institutions and domains of knowledge revealing the United States' dominance in this sector. Louis R. Iverson has attained a mean citation score of 104.17 from 6 articles as the significant influence of American academics in agro-meteorological investigations.

European contributions are significant, with Philippe Ciais from France and Wulf Amelung from the University of Bonn, Germany, being prominent figures. Ciais's work exhibits a significant citation impact, but Amelung's contributions, averaging a citation score of 21.83 across six publications demonstrating a steady yet comparatively moderate influence. Robert A. Marchant from the University of York in the United Kingdom has authored 8 papers, garnering 385 citations with an average score of 48.13.

Institutions with the most collaboration

Figure 6 illustrates the institutional partnership network in agro-meteorological services research, showcasing the interconnected relationships among leading universities and research institutions worldwide. Wageningen University & Research emerges as a key player, characterized by extensive collaborations with other major universities and organizations. Its central position in the network highlights its leadership in agro-meteorology and its role in fostering international research partnerships. Similarly, the University of Chinese Academy of Sciences plays a significant role, contributing

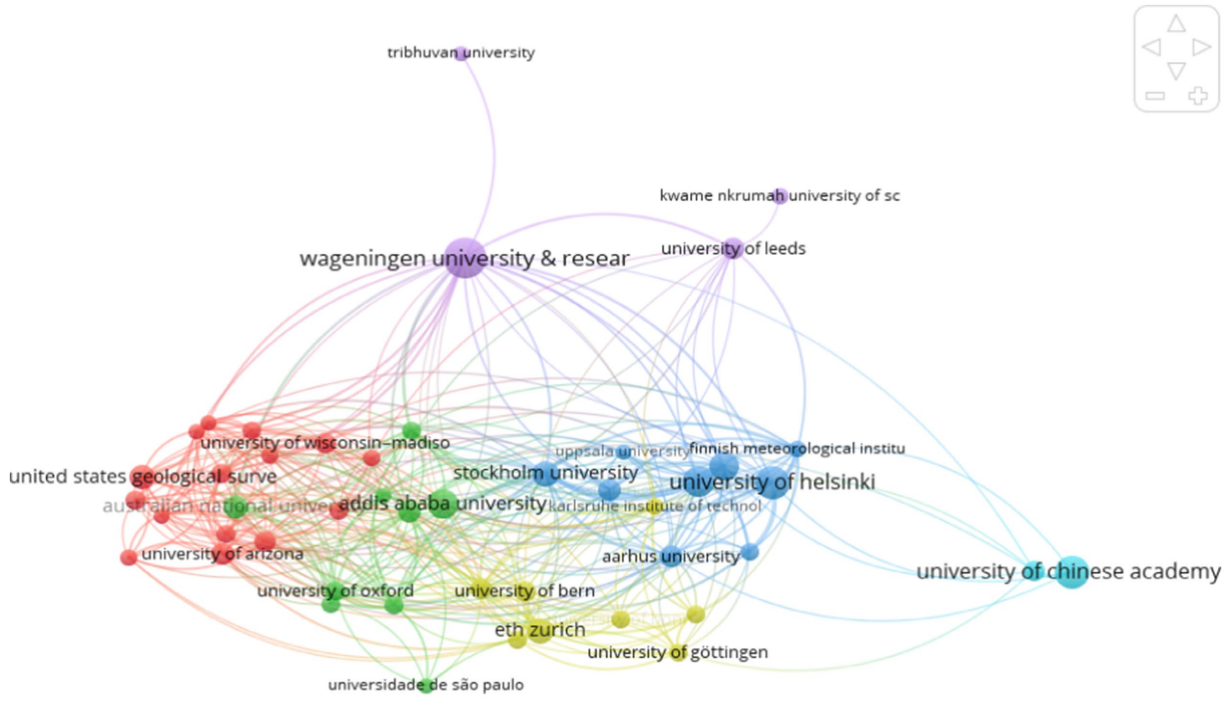

FIGURE 6
Institutional collaboration network in agro-meteorological services research.

TABLE 4 Collaborative publications and institutional impact correlation.

Collaborative publications	Institutional impact (Influence)	Correlation (*r*)	*p*-value
High	High	0.75	< 0.01
Moderate	Moderate		
Low	Low		

substantially to agro-meteorology research and exerting considerable influence within Asia.

The institutional collaboration network reveals several regional clusters. In Europe, institutions such as ETH Zurich, University of Göttingen, University of Helsinki, and Aarhus University form a strong and well-integrated research network. This reflects Europe's long-standing tradition of collaborative research and knowledge exchange in agro-meteorology. In North America, key contributors include the University of Wisconsin-Madison, the University of Arizona, and the United States Geological Survey (USGS), demonstrating extensive collaboration both within the region and with international partners.

In Africa, Addis Ababa University stands out as a prominent institution actively engaged in agro-meteorology research. Its collaborations with Western institutions indicate a strong commitment to localized enhancingclimate adoption strategies in African agriculture. Additionally, Kwame Nkrumah University of Science and Technology (KNUST) is increasingly integrating into the global research network, reflecting efforts to strengthen African institutions' participation in agro-meteorological research.

Beyond regional clusters, certain institutions play a pivotal role in bridging different research networks, facilitating the global transfer of knowledge. Wageningen University & Research and the University of Helsinki act as key knowledge hubs, connecting multiple regional clusters and promoting cross-continental research collaborations. Similarly, Stockholm University and the University of Leeds serve as essential links, enhancing the reach and influence of agro-meteorological services research worldwide. Even smaller institutions, such as Tribhuvan University in Nepal, contribute to region-specific research, often partnering with larger international institutions to strengthen their research impact.

Table 4 highlights a strong positive correlation ($r = 0.75$, $p < 0.01$) between the level of collaborative publications and institutional impact. This suggests that institutions engaging in higher levels of research collaboration tend to produce more influential and impactful research in agro-meteorological services.

Journals made the most significant contribution

The journal co-citation network offers a comprehensive perspective on the principal journals and thematic domains influencing agro-meteorological services research as revealed in

Figure 7. Sustainability stands out as a prominent journal showing its essential role in discussing sustainable agriculture practices, climate resilience, and resource management. The significance of Water within the network underlines the essential role of water-related research in agro-meteorology, especially in domains such as agricultural water management and agronomy. The Science of the Total Environment functions as a multidisciplinary nexus, integrating environmental, agricultural, and ecological research. The network displays several theme clusters, each signifying a particular focus area in agro-meteorology.

The red cluster, characterized by journals like Sustainability, Agricultural Water Management, and Frontiers in Sustainable Food, emphasises research on sustainable practices, resource efficiency, and climate adaptation in agriculture. This cluster is closely linked to the overarching objectives of agro-meteorology, especially in enhancing the efficiency of land and water resources while alleviating the effects of climate variabilty. The green cluster focusses on environmental and ecological aspects, with journals such as Global Change Biology, Biogeosciences, and Forests serving significant roles. This cluster presents the interrelation of agro-meteorological study with broader environmental science, especially in comprehending the interactions and repercussions of agriculture on natural systems.

The blue cluster emphasises geophysical and hydrological research, featuring notable journals like Remote Sensing, Reviews of Geophysics, and Hydrology and Earth System Sciences. This cluster demonstrates the consolidation of sophisticated technologies such as satellite remote sensing and hydrological modeling within agro-meteorology. These tools are progressively employed to assess climatic effects, enhance irrigation methods, and predict severe weather occurrences as an indication of the contribution of technical advancement to the discipline. Furthermore, journals such as The Science of the Total Environment and PLOS ONE hold crucial roles within the network, connecting various clusters and facilitating multidisciplinary research. Their robust interconnections across thematic domains underline the integration of environmental, agricultural, and social sciences within agro-meteorology. The connections between Remote Sensing and environmental and agricultural journals indicate an increasing dependence on satellite technologies for the observation of climate and agricultural systems.

Authors with the most citations

The visualization in the Figure 8 depicts a co-citation network of authors, emphasising prominent figures and their interrelations in agro-meteorological services research. Each node represents an author, with the size of the node indicating the frequency of citations, and the edges denoting co-citation relationships. Prominent nodes signify authors whose contributions are seminal or commonly cited, and clusters of nodes illustrate subject domains of inquiry. The results show that García-Ruiz and Lana-Renault (2011) stands out as the preeminent author in the network which characterized by the highest node size as a substantial influence on the subject. The robust associations between García-Ruiz and other writers indicate the foundational significance of their work. Asfaw et al. (2019) and

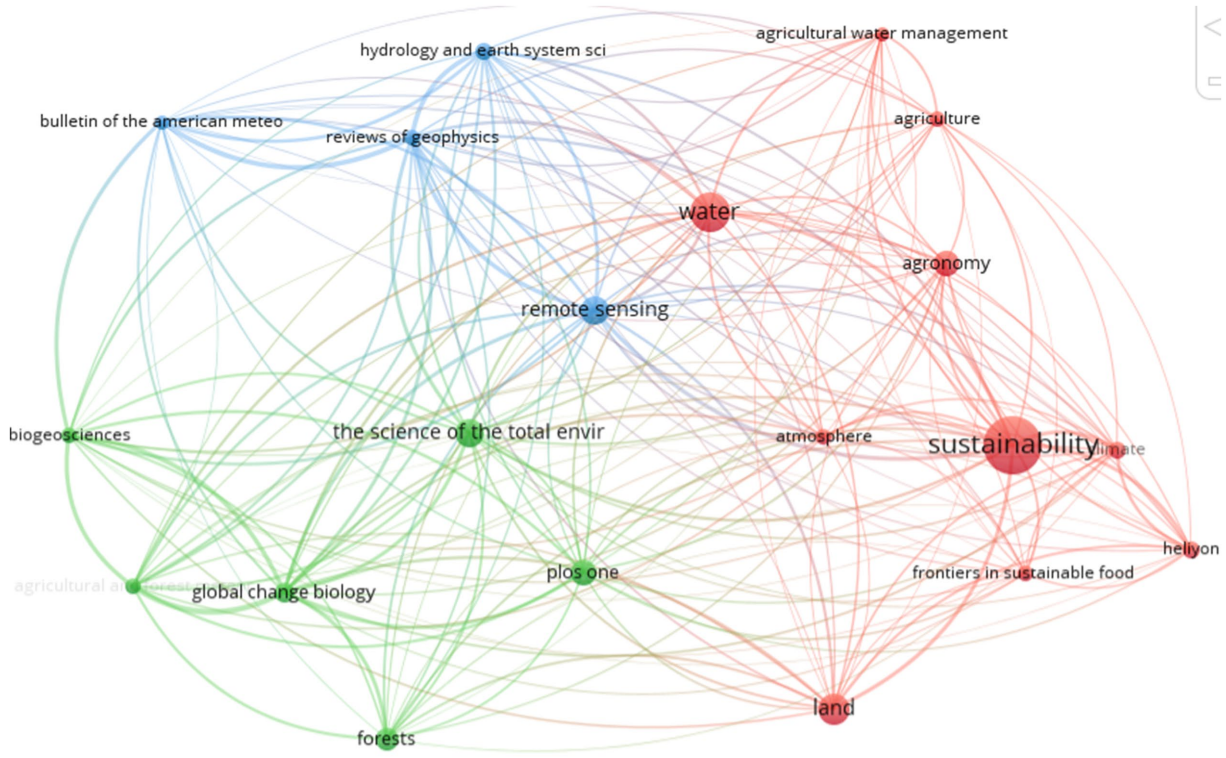

FIGURE 7
Journal co-citation network in agro-meteorological services research.

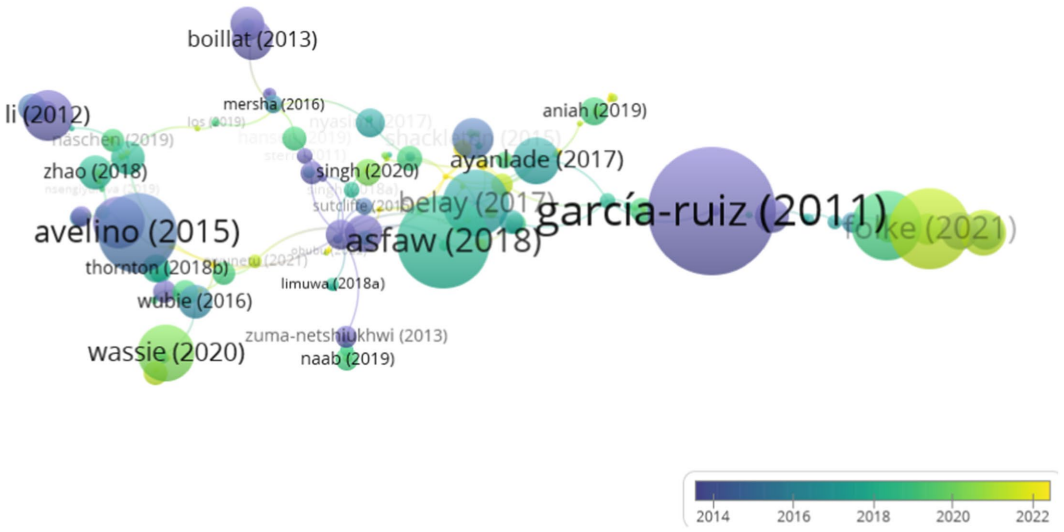

FIGURE 8
Author co-citation network in agro-meteorological services research.

Avelino et al. (2017) are likewise prominent personalities which illustrate their contributions to the comprehension of farmer adaptation techniques in agriculture.

The network displays multiple clusters, each signifying a unique thematic emphasis. The blue cluster, centred on García-Ruiz, pertains to interdisciplinary research concerning sustainability, agriculture, and the effects of climate alteration. The red cluster, with writers like Asfaw et al. (2019) and Aynalade (2017), concentrates on farmer behavior, adaption techniques, and the socio-economic aspects of agro-meteorology. Concurrently, the green cluster, which includes authors such as Avelino et al. (2017) and Wassie (2020), highlights agro-ecological research, specifically focussing on ecosystem services, crop diversification, and water management. Minor nodes, exemplified by Li (2012) and Boillat (2013), denote specialized contributions linked to the broader theme clusters. The existence of recent publications, such Foké (2021) and Wubie (2016), signifies continuous progress and their incorporation with core research. This co-citation network reveals the interdisciplinary and collaborative essence of agro-meteorological research. Foundational writers such as García-Ruiz and Lana-Renault (2011) establish the discipline, while contemporary contributions broaden the focus to tackle developing difficulties in climate-resilient agriculture. The robust co-citation linkages among authors illustrate the cumulative and interrelated advancement of knowledge in agro-meteorological services research.

Discussion

Research in agro-meteorological services is undergoing substantial expansion, as indicated by the trends, collaborations, and theme networks reflected in the data. Publications on agro-meteorological services rose steadily from 2010 to 2024. This reflects growing recognition of their importance in addressing climate variability's impact on agriculture. In 2020, publications peaked at over 171. This surge was likely driven by increased awareness of climate issues, global efforts toward sustainable development goals, and the COVID-19 pandemic's exposure of food system vulnerabilities (Mardones et al., 2020; Rasul, 2021; Paudel et al., 2023).

This time signifies intensified endeavors to incorporate agro-meteorological instruments into comprehensive frameworks such as climate-smart agriculture to enhance food security and fortify resistance against extreme weather phenomena. The stabilization of publications beyond 2020 indicates a transition toward the enhancement and implementation of research, emphasising localized solutions, including farmer-centric services and advanced technology to facilitate effective adaptation to climate problems. Faghih et al. (2022) and Fattahi et al. (2025) argued that the use of advanced technology is widely regarded by most users as an effective and efficient method of information dissemination, suitable for diverse user groups.

The keyword co-occurrence network elucidates the prevailing themes and priorities within the discipline. The significance of "climate change" presents its essential function while emphasising the need for agro-meteorological services to mitigate its effects on agricultural systems. The relationships among "climate change," "farmer," and "adaptation" also illustrate the growing emphasis on tailored solutions for farmers, in accordance with global initiatives aimed at empowering smallholder farmers who are particularly vulnerable to climatic variability. This corresponds with research conducted by Asfaw et al. (2019) and Wassie (2020), which discovered the significance of comprehending farmer behaviors, adaption strategies, and the incorporation of localized knowledge to enhance the adoption of

agro-meteorological technologies. The inclusion of phrases associated with environmental factors, such as "temperature," "precipitation," and "forest," indicate the interdisciplinary character of agro-meteorology, which amalgamates meteorology, ecology, and agriculture to formulate comprehensive solutions for mitigating climate hazards. Furthermore, phrases like "sustainability" and "research" indicate an increasing focus on meta-analyses, assessments, and theoretical progress to synchronize agro-meteorological services with sustainable development objectives.

The network of institutional collaboration shows the international scope of agro-meteorological research. Prominent institutions like Wageningen University & Research and the University of Chinese Academy of Sciences serve as essential centres, connecting regional clusters and promoting international collaborations. These relationships are especially important in linking affluent countries, which lead in research production, with at-risk areas like sub-Saharan Africa and South Asia. Institutions like Addis Ababa University and Kwame Nkrumah University of Science and Technology demonstrate the increasing participation of African entities in global research, frequently emphasising localized strategies for agricultural climate resilience. Nonetheless, the limited connections of smaller institutions such as Tribhuvan University in Nepal specify disparities in participation and resource accessibility. It indicates the necessity for enhanced capacity-building initiatives and equitable partnerships to facilitate greater contributions from developing regions. As Roth et al. (2010) concluded collaborative initiatives among prominent institutions can promote information transfer, bolster local research capabilities, and improve the efficacy of agro-meteorological services in mitigating region-specific agricultural vulnerabilities.

Furthermore, the rising research output from sub-Saharan Africa and South Asia underlines the pressing necessity to tackle the distinct difficulties encountered by these regions. Farmers in sub-Saharan Africa contend with unpredictable rainfall, recurrent droughts, and restricted access to technology, which intensify food insecurity (Emediegwu et al., 2022; Singh et al., 2018). In response to these challenges, agro-meteorological research has resulted in the creation of practical tools, including mobile applications that provide localized weather forecasts and agricultural recommendations. The 'Agro-Weather' application in Kenya has enabled smallholder farmers to enhance their agricultural practices, leading to increased crop yields and greater resistance to climatic variability (Atsiaya et al., 2022). In South Asia, where monsoon variability and water scarcity present considerable challenges (Rasul, 2021), satellite-based technologies such as the 'CropSAT' platform in India offer real-time data on crop health and soil moisture, allowing farmers to make informed decisions regarding irrigation and resource management (Kumar, 2020). These efforts demonstrate the translation of research into practical solutions that directly benefit local populations, highlighting the necessity of sustained investment in region-specific agro-meteorological services.

The journal co-citation network provides insights into the thematic and multidisciplinary dimensions of agro-meteorological research. Journals such as Sustainability, Water, and The Science of the Total Environment serve as pivotal platforms for the dissemination of research. This illustrates the convergence of sustainability, resource management, and interdisciplinary methodologies. The prominence of Sustainability emphasizes the sector's convergence with global aspirations to reconcile agricultural productivity, environmental preservation, and climate adaptation. Water and Agricultural Water Management present the essential importance of optimising water resources, particularly in areas where agriculture relies heavily on reliable water supply, such as South Asia and sub-Saharan Africa. The green and blue clusters demonstrate the amalgamation of ecological and technological viewpoints, with publications such as Global Change Biology and Remote Sensing showing studies on ecosystem effects and the utilization of sophisticated instruments like satellite imaging for monitoring and decision-making.

The incorporation of technical innovations such as remote sensing and Geographic Information Systems (GIS) into agro-meteorological services presents significant promise; yet, their implementation, particularly in resource-constrained environments, necessitates thorough critical analysis. Although these tools improve accuracy and scalability in agricultural decision-making (Carter and Oroy, 2024; Pan et al., 2022), their deployment in areas like sub-Saharan Africa is obstructed by considerable obstacles, such as inconsistent electricity, inadequate internet access, and insufficient technical proficiency (Paparrizos et al., 2024). Notwithstanding these obstacles, the advantages are clear: remote sensing has facilitated real-time observation of soil moisture and crop vitality in regions lacking meteorological stations, exemplified in rural India where satellite-derived vegetation indices have enhanced irrigation efficiency (Kumar, 2020). Likewise, GIS has assisted smallholder farmers in East Africa by delineating soil and water resources for enhanced management (Atsiaya et al., 2022). Nonetheless, accessibility and cost persist as essential concerns, frequently disregarded in favor of technological optimism. Practical instances, such as economical satellite instruments in Kenya or community-led GIS projects in India, highlight both the potential and the ongoing deficiencies in adoption (Singh et al., 2018; Wellstead et al., 2024). The existence of multidisciplinary journals like PLOS ONE offers a growing emphasis on comprehensive research that integrates environmental, agricultural, and social sciences, hence propelling the discipline forward. Mathur et al. (2019) assert that the emphasis on multidisciplinarity in any research domain is pivotal, as it serves as a critical driver for the growth and advancement of that field.

The author's co-citation network identifies the key contributors who have influenced the field of agro-meteorological study. García-Ruiz and Lana-Renault (2011) is a pivotal figure, with their research being referenced as fundamental for comprehending land use, sustainability, and agricultural adaptability. Asfaw et al. (2019) and Avelino et al. (2017) are significant contributors to farmer-centred adaptation solutions and socio-economic resilience. The fundamental works constitute the intellectual underpinning of the area, whilst recent contributions, such as those by Wassie (2020), demonstrate continuous progress and the incorporation of novel techniques and technologies. The categorization of authors into topic domains ensures

the variety of study interests, encompassing socio-economic aspects, ecological considerations, and technical applications (Rajumesh, 2024; Weltin et al., 2018). Nonetheless, the preeminence of earlier foundational studies indicates that although past investigations have profoundly influenced the discipline. Therefore, there is an increasing necessity for contemporary, high-impact research to tackle rising difficulties in agro-meteorology.

Notwithstanding these improvements, considerable hurdles persist in guaranteeing the equitable implementation and accessibility of agro-meteorological services. The preeminence of developed countries in research production and institutional partnerships illustrates inequalities in resource availability and research capability, especially in areas severely impacted by climate variabilty (Weltin et al., 2018). Enhancing the involvement of institutions from poor nations, while cultivating equitable collaborations with premier research centres, is essential for closing these disparities (Verhoeven, 2011). Moreover, although the incorporation of modern technologies is initiating a transformation in agro-meteorological services, it is imperative to guarantee that these innovations are accessible and applicable for smallholder farmers, especially in resource-limited environments (Faghih et al., 2022). Research indicates that the amalgamation of indigenous knowledge with sophisticated instruments enhances the uptake and efficacy of these services (Carter and Oroy, 2024). Furthermore, tackling systemic obstacles, including gender inequalities in access to climate information, is crucial for guaranteeing that agro-meteorological services equally benefit all stakeholders (Alubi et al., 2024; Atsiaya et al., 2022; Carr and Owusu-Daaku, 2016).

Addressing the existing knowledge gaps in agro-meteorological services requires a nuanced understanding of the complexities involved, particularly when integrating indigenous knowledge. One significant challenge is that traditional agricultural practices, often passed down orally, may lack the formal documentation necessary for scientific validation. This gap highlights the need for a robust framework that fosters trust between researchers and local communities, which is crucial for the successful incorporation of indigenous insights into scientific methodologies. Research by Partey et al. (2018) illustrates the potential of participatory approaches in West Africa, where local farmers' traditional indicators of weather patterns were effectively integrated into climate forecasting models. The persistent issue of gender inequality in accessing climate information services is a significant concern that warrants critical attention. Women often face systemic barriers that hinder their ability to access vital climate-related information, primarily due to limited educational opportunities and restricted access to technology. These disparities not only exacerbate existing inequalities but also impede women's ability to effectively respond to climate challenges. To address this pressing issue, it is essential to implement.The findings of this study offer an extensive overview of the growth, cooperation, and topic goals in agro-meteorological services research. The discipline has made considerable progress in tackling climate concerns, with substantial contributions from prominent scholars, organizations, and journals. Nevertheless, ongoing endeavors are essential to foster diversity, utilize developing technology, and guarantee that research findings convert into practical, localized solutions.

Implications

The results of the agro-meteorological services research include considerable significance for both scholarly and practical fields, especially in relation to climate resilience, food security, and sustainable agricultural growth. These implications encompass policy-making, research agendas, and practical applications, emphasising inclusivity, technological integration, and tangible solutions. The increase in publications and the prominence of subjects like climate change adaptation and sustainability reveal the essential function of agro-meteorological services in fulfilling global objectives, especially Sustainable Development Goals (SDGs) 2 (Zero Hunger) and 13 (Climate Action). Policymakers can leverage these findings to prioritize investments in agro-meteorological services and synchronize national agriculture strategy with global sustainability goals. The interdisciplinary aspect of the area highlights the necessity for cohesive policies that connect agriculture, climate adaptation, and environmental protection to guarantee comprehensive and successful solutions.

Moreover, the results of this study highlight the practical and policy complications of international cooperation and topical trends in agro-meteorological research. Partnerships between institutions in developed and developing countries have significantly advanced the creation and execution of localized agro-meteorological services. Collaborations between Wageningen University & Research and Addis Ababa University have produced customized weather advisory systems for smallholder farmers in Ethiopia, thereby improving their resilience to climate unpredictability (Partey et al., 2018). The significant emphasis on sustainability has impacted policy decisions, as seen by the incorporation of climate-smart agriculture methods in national policies throughout South Asia (Rasul, 2021). These connections are essential for capacity building, evidenced by the substantial increase in research output from institutions in sub-Saharan Africa and South Asia ($r = 0.85$, $p < 0.01$), which is crucial for promoting locally pertinent research and solutions. Nonetheless, converting these academic discoveries into extensive practical applications poses difficulties, especially in vulnerable areas where inadequate infrastructure and financing hinder implementation. To address this disparity, it is essential to cultivate inclusive collaborations that emphasize technology transfer, capacity building, and policy frameworks customized to the specific requirements of these areas.

The findings further indicate that although developed countries predominate in research output, enhancing collaboration with institutions in underdeveloped countries is crucial for tackling region-specific difficulties. For instance, regions at risk, such as sub-Saharan Africa and South Asia, where agriculture is particularly vulnerable to climatic fluctuations, require improved research capabilities and tailored agro-meteorological services. Therefore, enhancing collaborations between prominent research centres and institutions in various areas is essential in promoting the exchange of knowledge, resources, and technology to bolster agricultural resilience and productivity.

Moreover, findings underscore the necessity of addressing systemic hurdles, including gender inequities and inequitable

TABLE 5 Key knowledge gaps in agro-meteorological services research.

Knowledge gap	Evidence from analysis	Potential research direction
Underrepresentation of certain regions	Lower publication output from sub-Saharan Africa and South Asia compared to developed regions (Table 2)	Conduct localized studies in climate-vulnerable regions to develop context-specific solutions
Limited focus on gender disparities	Peripheral position of gender-related terms in the keyword co-occurrence network (Figure 3)	Investigate how gender dynamics influence access to and adoption of agro-meteorological services
Integration of indigenous knowledge	Smaller node size for "indigenous knowledge" in the keyword co-occurrence network (Figure 3)	Explore methodologies for integrating indigenous knowledge with scientific approaches
Technological accessibility in resource-limited settings	Implicit in challenges discussed but not directly analyzed in the bibliometric data	Develop and test low-cost, user-friendly technological solutions for farmers in developing regions
Limited integration of social sciences	Fewer publications in Human Society (369) compared to Environmental Sciences (957) (Figure 4)	Promote interdisciplinary studies combining meteorological data with socio-economic factors

access to climate information, which impede the effective use of agro-meteorological services. Programs and policies must guarantee inclusivity, emphasising the empowerment of marginalized groups, such as women and smallholder farmers, by enhancing access to education, training, and resources pertaining to climate and weather services.

Identified knowledge gaps

Our bibliometric study indicates that agro-meteorological services research has grown notably, especially in the fields of sustainability, climate adaptation, and international cooperation. Still, several significant subjects remain unaddressed. The published trends, keyword co-occurrence networks, and regional contributions all point up the noted knowledge deficits, which imply topics for more study meant to solve urgent concerns in the sector. Table 5 shows the main knowledge gaps, supporting data from the study, and future directions for continuous research.

The knowledge gaps found indicate contradictions and under-researched issues important for the development of agro-meteorological services. Though research output from South Asia and sub-Saharan Africa has risen ($r = 0.85$, $p < 0.01$), these areas remain underrepresented relative to developed countries, indicating that more concentrated studies are required to tackle their particular agricultural and climate issues. The marginal relevance of gender-related terms in the keyword network suggests that gender inequalities in service access and use are not well researched, thus research on gender-sensitive solutions is required. Participatory research is required since the thematic clusters' reduced focus on "indigenous knowledge" implies a lack of awareness of how traditional practices could improve service delivery. Moreover, while remote sensing and other technological developments are well-known, their use in low-resource environments raises questions and calls for creative, scalable solutions. The underrepresentation of social sciences in relation to natural sciences emphasizes the need of multidisciplinary approaches combining socio-economic factors with meteorological data. This study identifies gaps and links them to the trends and patterns seen in our analysis, therefore providing a framework for future research and ensuring that efforts focus on the most crucial and understudied domains in agro-meteorological services.

Conclusion

The bibliometric analysis of agro-meteorological services research from 2010 to 2024 reveals significant growth and a shift in research priorities, driven largely by the increasing challenges posed by climate change. This study underscores the rising importance of agro-meteorology in improving agricultural resilience, enhancing food security, and facilitating climate adaptation strategies. The research highlights the steady increase in publications, particularly after 2019, and identifies key thematic areas such as climate change, farmer adaptation strategies, and environmental variables, which are central to the discipline.Notably, the findings emphasize the global and interdisciplinary nature of agro-meteorological research, with significant contributions from institutions across both developed and developing regions. Collaborative efforts, particularly between institutions in Europe, North America, and sub-Saharan Africa, demonstrate the need for a collective response to the challenges of climate change and its impact on agriculture. The analysis also highlights emerging regions, such as South Asia and sub-Saharan Africa, whose increasing research output suggests a growing awareness and response to local climate challenges.

Furthermore, the study reveals the pivotal role of prominent journals and institutions, such as Wageningen University & Research and the University of Chinese Academy of Sciences, in shaping the direction of agro-meteorological services research. The collaboration networks identified in this study emphasize the critical role of international partnerships in fostering knowledge exchange and developing innovative solutions for climate-resilient agricultural systems. Therefore, while progress has been made in agro-meteorological research, the study points to the need for further capacity building, particularly in developing regions, and the integration of indigenous knowledge. Strengthening partnerships, advancing interdisciplinary research, and promoting inclusive collaborations will be key in addressing the emerging challenges posed by climate change to global agricultural systems.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

SK: Conceptualization, Data curation, Formal analysis, Methodology, Resources, Writing – original draft. EN: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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