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Water Management in Agriculture: A Bibliometric Analysis of Irrigation Practices and Sustainable Resource Use

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ABSTRACT

This study examines global research trends in water management for agriculture using a bibliometric approach based on the Scopus database (2000–2025). The analysis identifies irrigation efficiency, groundwater conservation, soil salinity management, and sustainable agricultural practices as core themes shaping the field. Keyword evolution shows a clear transition from early hydrological and resource-based studies to contemporary research emphasizing precision irrigation, IoT-enabled water monitoring, and climate-resilient farming systems. Collaboration networks reveal India, China, and the United States as leading contributors to scientific production, supported by strong partnerships across Europe, Asia, and Africa. Institutional mapping highlights the role of major research bodies such as ICAR, CSIRO, and ICARDA in advancing interdisciplinary knowledge. The findings underscore the need for integrated policy strategies, adoption of smart irrigation technologies, and enhanced soil–water management to address global water scarcity and food security challenges. While limited by database scope and algorithmic constraints, this study provides a comprehensive overview of developments in agricultural water management and offers a foundation for future research and policy formulation.

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1. INTRODUCTION

Agriculture has always been fundamentally dependent on the availability, distribution, and efficient use of water resources. In many agrarian economies, water determines not only crop productivity but also the stability of food systems and the sustainability of rural livelihoods [1]. Historically, irrigation infrastructures from ancient canal networks to modern drip systems evolved as a response to fluctuating climates and increasing food demands [2], [3]. As global populations continue to rise, the pressure on agricultural water systems intensifies, making water management a key determinant of national food resilience [4]. The linkage between water, food, and human survival reinforces the strategic importance of developing an integrated approach to manage water sustainably across agricultural landscapes.

Over the past two decades, climate change has emerged as a major disruptor of water availability in agricultural regions.

Frequent droughts, unpredictable rainfall, and extreme weather events reduce the reliability of surface and groundwater sources, creating uncertainty for farmers relying on consistent water supply [5], [6]. This shift in climatic patterns forces farmers to rethink conventional irrigation calendars and adopt more adaptive water-use strategies. Studies show that climate variability contributes to nearly 40% of annual yield losses in rain-fed agricultural zones [7]. As such, the challenge of irrigation efficiency is no longer merely a technical matter but a strategic adaptation to ecological instability.

Technological advancements have reshaped how water is utilized within farming systems. Modern irrigation methods such as drip irrigation, precision sprinklers, soil-moisture sensors, and IoT-based water monitoring, enable farmers to optimize water usage per hectare [8], [9]. These innovations reduce wastage and increase water-use efficiency, especially in areas with limited access to freshwater. However, technological uptake remains uneven across regions. Many smallholder farmers still rely on traditional irrigation practices due to limited knowledge, financial barriers, and infrastructure gaps [10]. Consequently, the effectiveness of water management becomes contingent on socio-economic factors and institutional support, not just technological advancement.

Another critical dimension is the governance and institutional arrangements governing water allocation. In several countries, agricultural water use is regulated through a combination of formal policies and informal community-based water rights. The coordination among farmers, irrigation authorities, and local governments determines how equitably and sustainably water resources are shared [11], [12]. Weak institutional oversight may lead to over-extraction of groundwater, conflicts between upstream and downstream users, and deterioration of water quality. Conversely, well-designed water management frameworks supported by clear rules and monitoring systems, have been shown to conserve water and improve agricultural output [13]. This governance perspective highlights that water management is also a social and political process.

Lastly, sustainability concerns amplify the urgency of effective water management in agriculture. The agricultural sector contributes significantly to global water consumption, accounting for nearly 70% of freshwater withdrawals worldwide [14], [15]. Mismanagement of water can degrade ecosystems, reduce biodiversity, and accelerate soil salinization particularly in irrigated lands. Sustainable water management promotes conservation practices such as rainwater harvesting, groundwater recharge, wastewater reuse, and ecological restoration of watersheds. These practices ensure that agricultural productivity can increase without compromising environmental integrity or future water availability. Thus, achieving sustainable agricultural growth requires a long-term vision that harmonizes production demands with ecological stewardship.

Despite the recognized importance of efficient water management, agricultural sectors across many regions continue to face persistent challenges related to water scarcity, inefficient irrigation practices, and weak institutional coordination. Inadequate access to sustainable irrigation technologies forces farmers to rely on water-intensive methods, resulting in high wastage and low water-use efficiency. Climate variability exacerbates these issues by causing unpredictable water supply, often pushing farmers into cycles of crop failure and financial vulnerability. At the governance level, fragmented policies and limited enforcement create disparities in water allocation and lead to unsustainable extraction of groundwater. These conditions collectively hinder agricultural productivity, threaten food security, and compromise ecological sustainability.

This study aims to examine the dynamics of water management in agriculture by analyzing the environmental, technological, and institutional factors that shape water-use efficiency and sustainability. Specifically, the research seeks to: (1) identify the key challenges faced by farmers in accessing and managing agricultural water resources; (2) investigate the role of modern irrigation technologies and innovations in improving water efficiency; and (3) evaluate how governance structures and policy frameworks influence sustainable water allocation. Ultimately, this study intends to provide strategic insights and recommendations to enhance water management practices that support resilient agricultural systems and long-term environmental sustainability.

2. METHODS

This study employed a bibliometric and qualitative content analysis approach to examine global research trends on water management in agriculture. The bibliometric component was conducted using the Scopus database, chosen due to its comprehensive indexing of peer-reviewed publications across agriculture, hydrology, environmental science, engineering, and sustainability fields. The search period was restricted to 2000–2025 to capture developments in water management over the past twenty-five years, including technological advancements, climate change adaptation strategies, and governance reforms. Search strings such as "water management," "agricultural irrigation," "water efficiency," "sustainable agriculture," and "water governance" were applied in title, abstract, and keyword fields. Publications selected included articles, reviews, conference papers, and book chapters to ensure holistic coverage. Duplicate records were removed, and only English-language documents were included for consistency.

After data retrieval, bibliometric indicators were generated to examine publication trends, leading authors, prolific countries, institutional contributions, and dominant keywords. Tools such as VOSviewer and Bibliometrix R were utilized to map co-authorship networks, keyword co-occurrence, citation patterns, and thematic evolution within the field. These tools allowed the study to visualize conceptual clusters related to irrigation technology, climate adaptation, water policy, and sustainable farming practices. In addition to quantitative mapping, a screening protocol was applied to identify the most influential and highly cited papers for deeper qualitative interpretation. This ensured that the analysis not only captured statistical patterns but also reflected the intellectual structure of the field [16], [17], [18].

To complement the bibliometric results, a qualitative content analysis was conducted on selected key publications to derive deeper insights into methodological trends, theoretical foundations, and practical issues related to agricultural water management. The analysis focused on recurring themes such as irrigation efficiency, resource governance, farmer adaptation behavior, and sustainability frameworks. Coding procedures followed an inductive approach, allowing themes to emerge naturally from the literature. Integrative synthesis was then performed to connect bibliometric findings with qualitative insights, thereby producing a comprehensive understanding of how water management in agriculture has evolved from 2000 to 2025. This mixed-method strategy strengthened the validity of the study and enabled a richer interpretation of contemporary challenges and opportunities in sustainable water management.

3. RESULTS AND DISCUSSION

3.1 Keyword Co-Occurrence Network

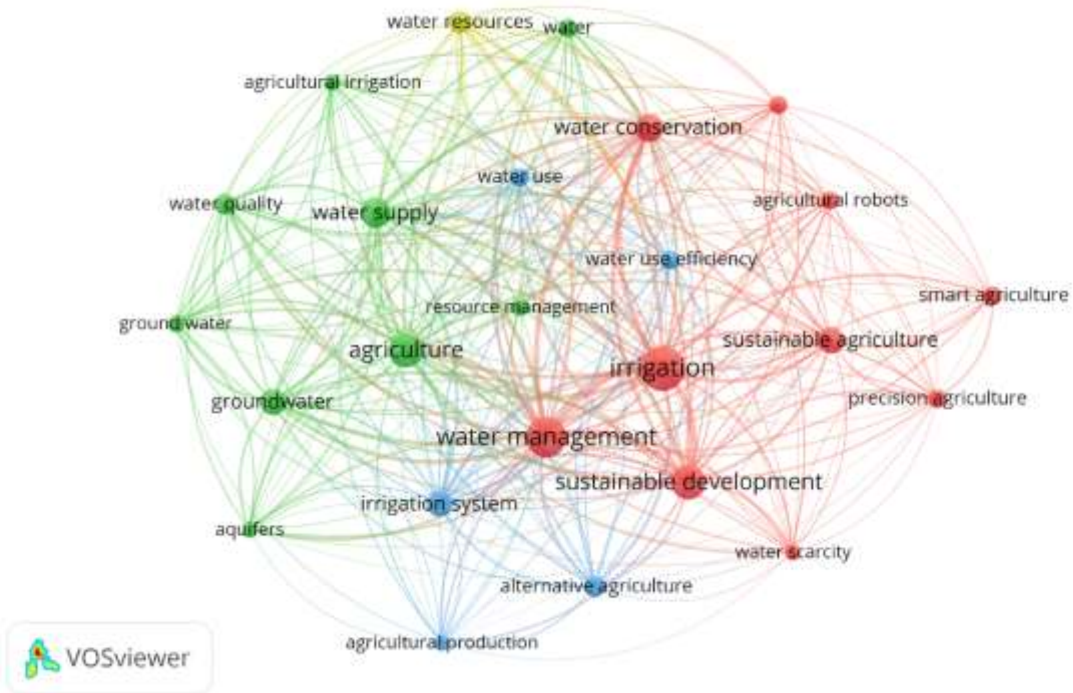

Figure 1. Network Visualization
Source: Data Analysis Result, 2025

The VOSviewer map illustrates the conceptual structure of research on water management in agriculture, revealing four major keyword clusters that reflect distinct thematic domains within the literature. The red cluster, centered on *irrigation*, *water management*, *sustainable development*, *water conservation*, and emerging terms like *precision agriculture*, *smart agriculture*, and *agricultural robots*, represents the integration of technological innovation with sustainability agendas. This cluster highlights a strong research focus on increasing water-use efficiency through advanced digital and automation technologies, aligning with global efforts toward climate-resilient agriculture. The green cluster, dominated by terms such as *water supply*, *agriculture*, *groundwater*, *aquifers*, and *water quality*, captures studies concerned with hydrological resources, groundwater extraction, and environmental monitoring. It suggests that water management research is strongly linked to ecological conditions, resource availability, and environmental protection. The blue cluster emphasizes *irrigation systems*, *agricultural production*, and *alternative agriculture*, reflecting research on improving traditional irrigation methods and exploring diversified farming systems that respond to water constraints.

Meanwhile, the smaller yellow cluster, which includes *water resources* and *water use*, links across all other clusters, indicating that these concepts serve as bridging themes in the broader discourse on water sustainability. The dense interconnections among clusters demonstrate that water management research is inherently multidisciplinary, combining hydrology, environmental sustainability, precision technologies, and agricultural productivity in a tightly integrated knowledge structure. Overall, the visualization suggests that contemporary research increasingly prioritizes sustainable irrigation practices, technological innovation, and the protection of groundwater systems as central pillars of effective agricultural water management.

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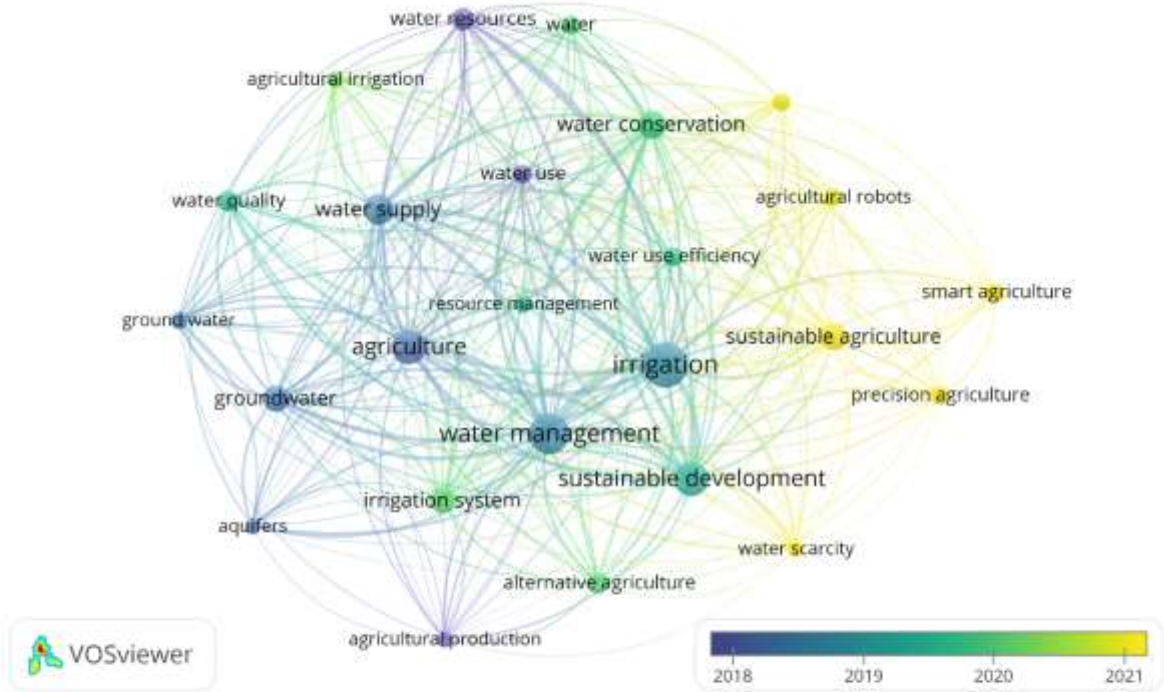

Figure 2. Overlay Visualization

Source: Data Analysis Result, 2025

The overlay visualization map illustrates the temporal evolution of research themes related to water management in agriculture from 2018 to 2021. In this figure, colors represent the average publication year of keywords: dark blue and purple indicate earlier research (2018), green reflects mid-period studies (2019–2020), and yellow represents the most recent research contributions (2021). This gradient allows us to observe how scientific attention has shifted from foundational hydrological topics toward emerging technology-driven themes in agricultural water management.

The earliest keywords, shown in dark blue and purple, cluster around concepts such as *groundwater*, *aquifers*, *water resources*, *irrigation system*, *agricultural production*, and *water supply*. These terms reflect long-standing concerns centered on the availability, extraction, and quality of freshwater sources, as well as the infrastructure used to distribute water for farming. Early research during this period focused strongly on understanding hydrological processes, monitoring groundwater depletion, and maintaining agricultural productivity under increasing water stress. The dominance of these foundational terms suggests that the initial research emphasis prioritized ecological and infrastructural dimensions of agricultural water management.

Research themes evolve into green-colored mid-stage keywords, including *water management*, *irrigation*, *water quality*, *water use*, *resource management*, and *sustainable development*. These represent a transition phase (2019–2020) in which studies began integrating sustainability concepts, shifting attention from merely securing water supply toward improving water-use efficiency and managing resources more holistically. The stronger interconnectedness among these mid-stage nodes indicates increasing interdisciplinary dialogue between hydrology, policy, sustainability science, and agricultural engineering. In this phase, researchers explored how integrated water resource management (IWRM), improvements in irrigation efficiency, and policy interventions could build resilience against climate variability and water scarcity.

The most recent research, highlighted in yellow, reveals a distinct shift toward technology-oriented and innovation-driven themes. Keywords such as *precision agriculture*, *smart agriculture*, *agricultural robots*, *water conservation*, *sustainable agriculture*, and *water use efficiency* dominate this cluster. Their emergence in the 2021 period suggests that current scientific attention has moved toward digitalization and automation in agriculture. These terms indicate a growing focus on advanced technologies—such as IoT-based irrigation sensors, AI-driven crop monitoring, and robotics—to optimize water consumption and enhance agricultural sustainability. The appearance of *water scarcity* in this latest cluster reinforces the urgency of addressing global water challenges through innovation. Collectively, this shift reflects the broader transformation of agricultural water management into a more data-driven, technology-enabled field aligned with sustainability goals.

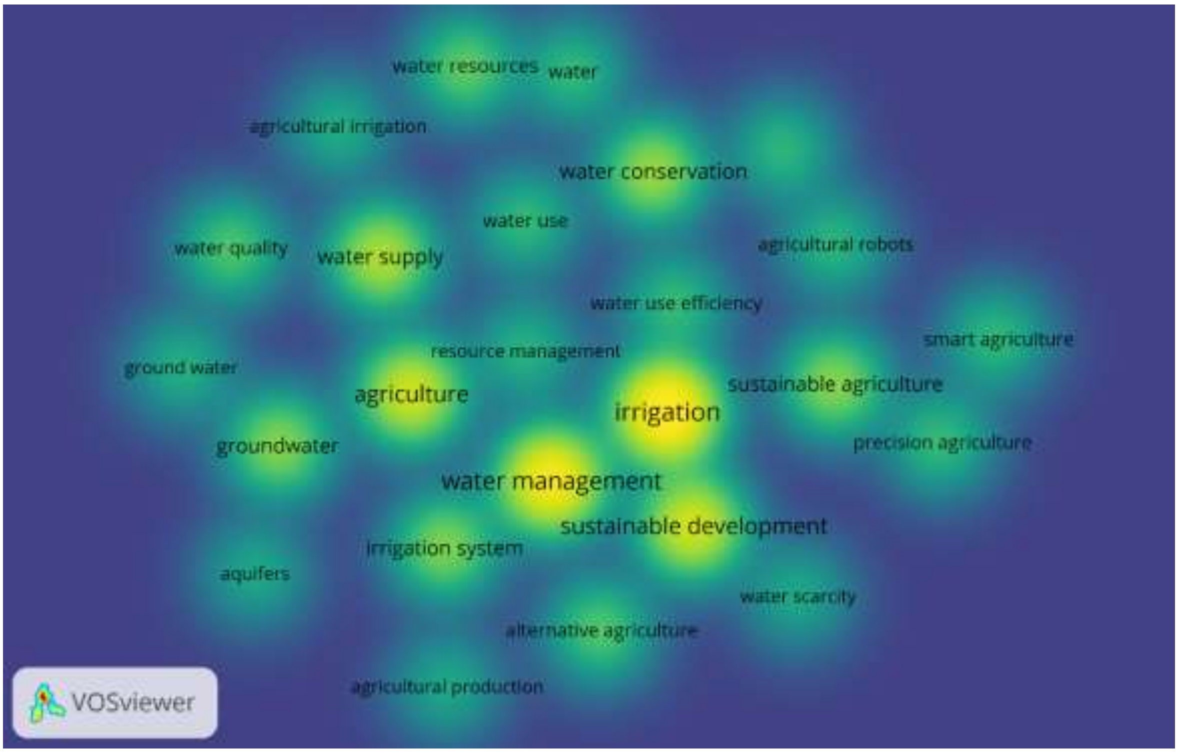

Figure 3. Density Visualization
Source: Data Analysis, 2025

The density visualization map highlights the most influential and frequently occurring research keywords in the field of water management in agriculture, with color intensity indicating the degree of research concentration. Yellow areas represent high-density hotspots where keywords appear most frequently and form the core of the literature, while green areas indicate moderate research attention, and blue or dark areas reflect relatively lower density and emerging or peripheral topics.

At the center of the map, the most intense yellow zones revolve around the keywords “irrigation,” “water management,” “sustainable development,” and “agriculture.” These terms form the intellectual core of the field, showing that research on agricultural water management is strongly anchored in improving irrigation systems, enhancing sustainability, and understanding broader agricultural implications. Their high density suggests they are the most widely cited and widely discussed concepts across the literature, making them central pillars of research activities.

Surrounding this core are several medium-density (green) themes that signify important but more specialized areas of study. These include "water supply," "water use," "water conservation," "water quality," "resource management," "groundwater," "aquifers," and "irrigation system." Their positioning indicates that scholars frequently link these concepts to the central theme of irrigation and water management. For example, groundwater and aquifers represent the primary sources of agricultural water, while water quality, conservation, and supply relate to the sustainability and efficiency of water usage. This cluster reflects an environmental-hydrological focus, emphasizing the management of natural water resources as a crucial foundation for agricultural sustainability.

On the periphery, lighter green areas highlight emerging and technology-oriented research topics, such as "precision agriculture," "smart agriculture," "agricultural robots," "water use efficiency," and "sustainable agriculture." Although these terms are not as densely represented as the core hydrology and irrigation terms, their growing visibility in the density map suggests increasing academic interest and rapid development. The inclusion of smart agriculture and robotic technologies indicates a shift toward digital transformation in agricultural water management, reflecting global trends in automation, sensor-based irrigation, and AI-assisted farming.

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3.2 Co-Authorship Network

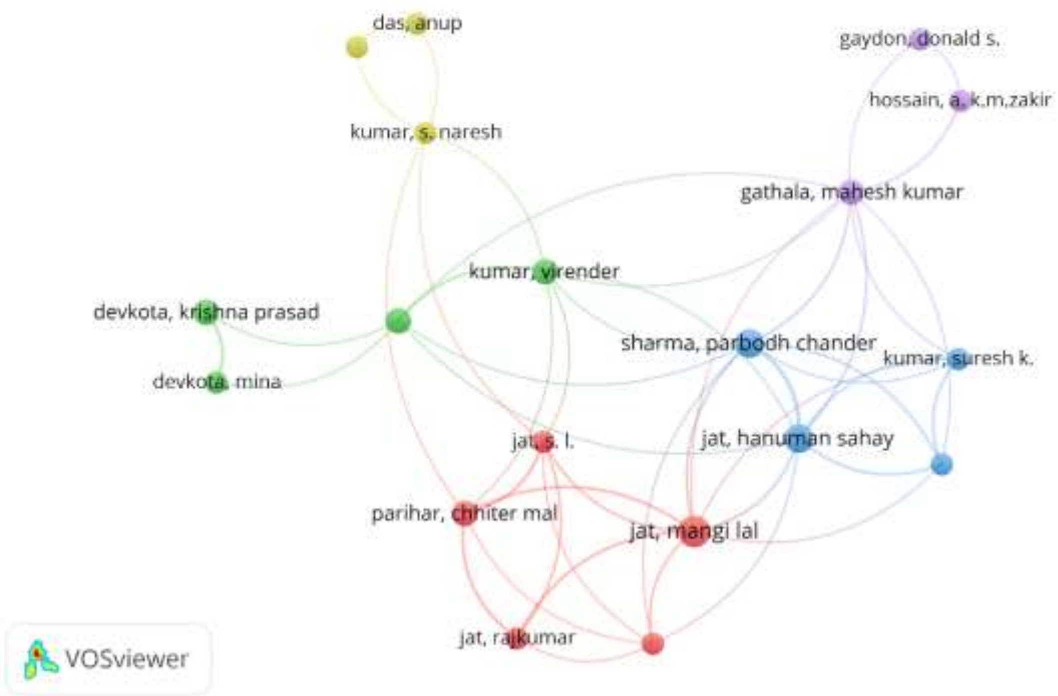

Figure 4. Author Collaboration Visualization

Source: Data Analysis, 2025

The co-authorship visualization map illustrates the collaborative relationships among researchers in the field of agricultural water management, with each color representing a distinct network cluster. The size of each node reflects the number of publications or citation strength associated with the author, while the connecting lines indicate the presence and strength of collaborative ties. Overall, the network demonstrates a moderately clustered structure, where multiple research groups work within their own circles but maintain several cross-cluster linkages that support knowledge integration across the field.

The largest and most interconnected cluster appears in red, centered around *Jat, Mangi Lal*, *Jat, S. L.*, *Parihar, Chhiter Mal*, and *Jat, Rajkumar*. This cluster represents a cohesive research team that works extensively on themes such as irrigation efficiency, sustainable cropping systems, and agricultural resource management. The dense links among these authors suggest long-term collaborative projects and shared institutional affiliations, likely contributing significantly to the field's foundational knowledge, especially in agronomy and irrigation technologies.

A second major cluster, colored blue, includes *Sharma, Parbodh Chander*, *Jat, Hanuman Sahay*, and *Kumar, Suresh K.*. This group appears strongly connected to the red cluster while maintaining internal collaboration. Their interlinkage with multiple other clusters indicates that they serve as bridging authors, connecting methodological developments (e.g., soil-water interaction, crop modeling) with broader sustainability and water management discussions.

The green cluster, containing *Kumar, Virender*, *Devkota, Krishna Prasad*, *Devkota, Mina*, and *Kumar, S. Naresh*, focuses on water conservation practices, groundwater usage, and agricultural irrigation efficiency. The strong internal ties among these authors suggest a robust research unit specializing in hydrological aspects of agricultural water management. Their indirect connections to the red and blue clusters indicate knowledge exchange, particularly on shared topics such as irrigation system optimization and water-saving techniques. On the upper right, the purple cluster includes *Gathala, Mahesh Kumar*, *Hossain, A.K.M. Zakir*, and *Gaydon, Donald S.*. This group appears slightly more isolated geographically or institutionally but maintains collaborations within the cluster. Their publications often relate to crop-water modeling, climate-resilient agriculture, and mechanization options for water conservation. This cluster represents international or cross-regional research partnerships, as indicated by the distinct connectivity pattern.

Finally, the yellow cluster, consisting of *Das, Anup* and *Kumar, S. Naresh*, suggests emerging collaborations or early-stage partnerships. The smaller size of these nodes and fewer links indicate that these authors contribute to specific niche topics and may be relatively newer entrants into the agricultural water management research domain. Their position connecting the green and red clusters illustrates a role in integrating hydrological studies with agronomic practices.

Figure 5. Affiliation Collaboration Visualization
Source: Data Analysis, 2025

The institutional co-authorship network map illustrates the collaborative relationships among research institutions working in the field of agricultural water management. Each node represents an institution, the size of the node reflects its publication or citation strength, and the colors represent distinct collaboration clusters. The connecting lines indicate co-authored publications or ongoing academic partnerships. Overall, the visualization reveals a structured yet interconnected global research network dominated by institutions from India, China, Italy, and international research centers.

The most prominent and densely connected cluster appears in red, centered around institutions such as ICAR – Indian Institute of Maize Research, ICAR – Indian Agricultural Research Institute, Punjab Agricultural University, and the Commonwealth Scientific and Industrial Research Organisation (CSIRO). This cluster represents a strong multidisciplinary collaboration group focused on irrigation, sustainable agriculture, and water-use efficiency. The presence of CSIRO indicates international involvement, suggesting that these Indian institutions maintain active research partnerships with global bodies in agricultural sustainability and water management science. To the left, the yellow cluster includes institutions such as ICAR – Indian Institute of Soil Science and ICAR – Indian Institute of Water Management. These institutions specialize in soil-water interactions, hydrology, and irrigation technologies. The relatively fewer links within the cluster compared to the red group suggest that these institutes function as specialized contributors rather than large collaborative hubs. Their strongest connections lead toward the red cluster, indicating that their expertise in soil and water science feeds directly into the broader agricultural sustainability research led by major ICAR bodies.

The blue cluster, which includes Northwest A&F University (China), represents another international collaboration group focusing on agricultural engineering, crop-water relationships, and water-saving irrigation technologies. This cluster's connections with the red group indicate active India–China collaboration, particularly regarding innovations in irrigation systems and agricultural hydrology. Toward the right side of the visualization, the purple cluster—featuring the International Center for Agricultural Research (ICARDA)—demonstrates the role of international organizations in facilitating cross-regional agricultural water management research. ICARDA's central position within its cluster and its multiple linkage lines suggest that it acts as a global connector, bridging Asian and European research networks through multidisciplinary development projects in water-scarce regions.

Further to the right, the green cluster includes institutions such as the Istituto Agronomico Mediterraneo (Italy), which represents the Mediterranean research community. This group focuses on climate-resilient agriculture, water-efficient farming systems, and sustainable resource management in arid and semi-arid regions. Although geographically distant, this cluster maintains connections with the purple cluster, indicating transnational collaborations in shared thematic areas like drought adaptation, irrigation optimization, and agricultural sustainability.

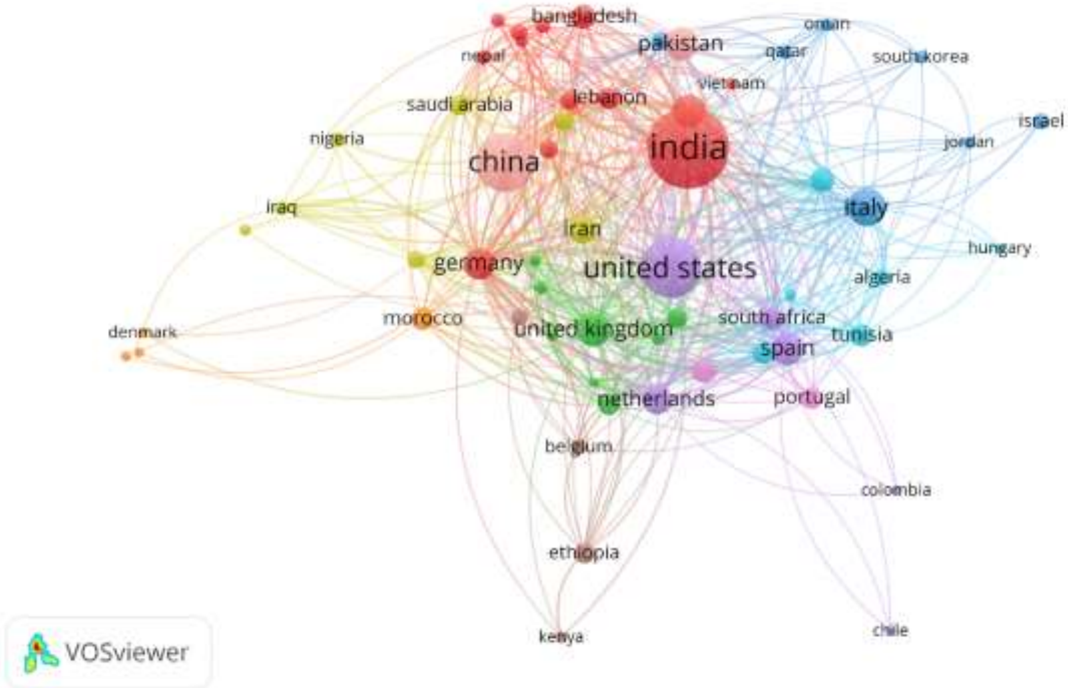

Figure 6. Country Collaboration Visualization
Source: Data Analysis, 2025

The country collaboration visualization map shows the global research network in agricultural water management, with each node representing a country and the size of each node reflecting publication volume or citation impact. The colors correspond to collaboration clusters, while the connecting lines indicate co-authorship links, demonstrating how nations contribute jointly to scientific advancements. At the center of the map, India, China, and the United States emerge as the most influential and productive countries, evidenced by their large node size and dense interconnections with multiple regions. Their central positioning reflects strong leadership in research domains such as irrigation technologies, groundwater management, precision agriculture, and sustainability frameworks.

The red cluster, dominated by India, includes countries such as Pakistan, Bangladesh, Nepal, Lebanon, and Saudi Arabia. This cluster reflects strong South Asian and Middle Eastern cooperation, likely due to shared challenges in water scarcity, population pressure, and agricultural intensification. India's role as the largest node indicates its status as a global hub in agricultural water management research, supported by large national research institutions and extensive regional collaboration. The yellow cluster, anchored by China, connects extensively with Germany, Nigeria, Iraq, and Morocco. These linkages suggest China's increasing role in international scientific partnerships, especially in the areas of irrigation modernization, soil-water interactions, and large-scale water management projects. Germany's presence in this cluster highlights Europe–Asia research partnerships, particularly in sustainability, water governance, and climate-resilient agriculture.

The green cluster is led by the United States, which collaborates closely with the United Kingdom, Netherlands, Belgium, South Africa, and Ethiopia. This reflects a strong North America–Europe–Africa collaboration network, driven by multidisciplinary expertise in hydrology, agricultural engineering, remote sensing, and climate adaptation. The United States functions as a central bridging actor, linking multiple clusters and supporting global knowledge dissemination. The blue cluster, centered on Italy, includes nations such as Algeria, Tunisia, Jordan, South Korea, Qatar, and Oman. This cluster reflects Mediterranean and Middle Eastern collaboration, often focused on drought management, sustainable agriculture, and efficient irrigation systems in arid climates. Italy's role as a leadership node suggests its contribution to research on water-efficient crop cultivation and climate-resilient farming.

Meanwhile, the purple cluster, represented by Spain, Portugal, Colombia, and Chile, highlights Ibero-American research collaborations. These countries share research interests in water-scarce environments, irrigation optimization, and soil-water conservation strategies, forming a secondary but important network in global water management studies.

3.3 Citation Analysis

The bibliometric data above identifies the ten most significant articles in the domain of Fear of.

Table 1. Top Cited Research

Citations	Authors and year	Title
1329	[19]	Agricultural sustainability: Concepts, principles and evidence
729	[20]	Regional strategies for the accelerating global problem of groundwater depletion
625	[21]	Improving agricultural water productivity to ensure food security in China under changing environment: From research to practice
531	[22]	Soil salinity under climate change: Challenges for sustainable agriculture and food security
412	[23]	Phytoremediation of Sodic and Saline-Sodic Soils
394	[24]	Smart water management platform: IoT-based precision irrigation for agriculture
384	[25]	Soil salinization management for sustainable development: A review
315	[26]	Effects of rainfall harvesting and mulching technologies on water use efficiency and crop yield in the semi-arid Loess Plateau, China
313	[27]	Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa
301	[28]	Nitrogen, sustainable agriculture and food security. A review

Source: Scopus, 2025

The table presents the ten most highly cited publications in agricultural water management, sustainability, and soil-water interactions, showing the intellectual foundations that have shaped this field over the past two decades. The highest-cited work, [19], serves as a seminal conceptual framework for agricultural sustainability, emphasizing ecological principles, long-term resource use efficiency, and integrated farming systems. Its prominence signals that sustainability thinking forms the theoretical backbone of research in water and agriculture. Closely following, [20] highlights the escalating global issue of groundwater depletion, marking a shift from general sustainability frameworks to resource-specific crises, particularly the overexploitation of groundwater for irrigation.

Several publications focus on improving water productivity and food security, highlighting the central role of irrigation efficiency. [21]connects water productivity research with national food security in China, showing how scientific advancements translate into practice under environmental change. This theme is reinforced by [29] and [27], both of which emphasize rainfall harvesting, mulching, and supplemental irrigation as adaptive strategies for semi-arid and drylands agriculture. Together, these works underscore how efficient use of limited water resources is a dominant research priority, especially in water-scarce regions.

Soil-related challenges also emerge prominently in this top-cited list. [22] and [25] represent modern concerns regarding soil salinity and its accelerating impact under climate change, linking soil degradation to broader water and food security issues. Similarly, [7] offers foundational insights into phytoremediation of saline-sodic soils, showing early attempts to integrate biological solutions into soil-water management. These works collectively demonstrate that soil water interactions are inseparable components of sustainable agricultural systems.

Technological innovation appears in the form of [24], which marks a transition toward digital agriculture, particularly IoT-based smart irrigation systems. This reflects a growing movement in recent years toward precision technologies that aim to optimize water application and reduce waste. Its presence in the list suggests the increasing influence of smart water management tools as agriculture shifts into an era of automation, data analytics, and real-time resource monitoring. Lastly, [28] highlights the role of nitrogen management in achieving sustainable agriculture, integrating nutrient efficiency with water and food security. This signals that agricultural sustainability research increasingly adopts multi-dimensional approaches, linking water, soil, nutrient cycles, and climate adaptation within integrated frameworks.

Discussion

The findings of this study reveal a dynamic and rapidly evolving landscape of research in water management for agriculture, shaped by growing environmental pressures, technological advances, and global efforts to achieve sustainable food systems. Across bibliometric analyses keyword mapping, temporal evolution, institutional collaboration, and country networks it becomes evident that agricultural water management has expanded from traditional irrigation concerns into a multidisciplinary field integrating hydrology, agronomy, climate change adaptation, soil science, and digital technologies. This evolution reflects a global recognition that water scarcity, groundwater depletion, and soil salinization threaten long-term food security, especially in climate-sensitive regions. Moreover, the emergence of precision and smart agriculture signals a paradigm shift toward data-driven and automated decision-making in the use of water resources.

A central finding from the keyword density map and high impact literature table is that irrigation, sustainable development, water management, and agriculture remain the intellectual core of the field. Studies like [19] and [21] have become foundational references, shaping conceptual frameworks around sustainability and demonstrating how improvements in water-use efficiency can influence national food security. The prominence of salinity management publications in recent years such as [22] and [25] indicates an increasing academic concern for soil-water interactions. This thematic shift reflects not only environmental realities but also the growing need to adapt agricultural systems to climate-induced water stress.

The temporal overlay visualization confirms this progression, showing that earlier research (2018) focused on groundwater, aquifers, and the physical availability of water, while more contemporary research (2021) centers on precision agriculture, smart irrigation, agricultural robotics, and water conservation technologies. This movement toward more technologically sophisticated themes demonstrates that the field is undergoing digital transformation. Automated irrigation platforms, IoT-based soil-moisture monitoring, and AI-enabled crop-water models are increasingly studied as future pathways to optimize water application and enhance agricultural resilience. These developments correspond with global sustainability agendas that call for integrated technological and ecological solutions to water scarcity.

The collaboration networks further reveal how research is geographically organized. India, China, and the United States act as major global nodes in agricultural water management research, demonstrating extensive international partnerships. These countries possess large agricultural sectors, diverse climates, and strong research infrastructures, enabling them to contribute significantly to global knowledge production. Meanwhile, Mediterranean and Middle Eastern countries uch as Italy, Tunisia, Jordan, Qatar, and Saudi Arabia form clusters focused on drought resilience and efficient water use in arid environments. These patterns suggest that scientific collaboration aligns strongly with shared environmental challenges and agroecological conditions. Institutions such as ICAR (India), CSIRO (Australia), Northwest A&F University (China), and ICARDA (international) play strategic roles in linking local water challenges to global research networks, strengthening the global flow of knowledge.

Taken together, these findings reinforce the idea that water management in agriculture is both a scientific and geopolitical concern. Research progress increasingly depends on cross-country cooperation, particularly where hydrological issues transcend national boundaries. This is especially relevant for groundwater aquifers, transboundary rivers, and climate, change, induced water stress, which require shared knowledge and coordinated strategies.

The study provides several practical implications for policymakers, agricultural practitioners, and water resource managers. First, the centrality of irrigation efficiency and sustainable water management highlights the urgent need for policy reforms that promote water-saving technologies. Governments should prioritize subsidies, extension programs, and training initiatives that support the adoption of drip irrigation, sprinkler systems, and precision irrigation technologies. These systems can help farmers reduce water wastage, increase crop productivity, and stabilize yields under uncertain climatic conditions. Second, the increasing prominence of digital agriculture in recent research suggests that IoT-based monitoring tools and smart irrigation platforms should be integrated into national agricultural development programs. Practical examples include sensor-based soil moisture systems, mobile applications for irrigation scheduling, and satellite-based water stress detection. Such technologies improve decision-making and enhance farmers' capacity to respond to fluctuations in rainfall, evapotranspiration, and soil-water availability. Third, the strong research emphasis on soil salinity and salt-affected lands indicates the need for targeted interventions in degraded ecosystems. Policymakers must support reclamation programs, drainage infrastructure, and salt-tolerant crop varieties, particularly in regions facing rising sea levels, reduced freshwater inflows, or poor-quality irrigation water. Extension services should be strengthened to disseminate best practices in soil-water management, mulching, and phytoremediation.

Finally, the global collaboration networks revealed in this study point to the importance of cross-country partnerships for tackling water scarcity. Governments, research institutions, and NGOs should strengthen transnational research exchange programs and regional water governance frameworks, especially in areas with shared aquifers or river basins. Strengthening these networks can accelerate innovation and ensure equitable access to successful irrigation technologies.

The study advances theoretical understanding in several ways. First, it demonstrates how agricultural water management has shifted from traditional hydrological perspectives toward a broader ecosystem-based and technology-integrated conceptualization. This supports an emerging theoretical synthesis that combines ecological resilience, digital farming systems, and sustainable development principles.

Second, the evolution of research themes captured through bibliometric visualization provides theoretical evidence for the transition from resource-based water management to knowledge- and technology-driven approaches. This transformation aligns with contemporary theories in sustainability science, particularly the adaptive systems framework and socio-technical transitions theory. Third, the study offers a theoretical contribution by illustrating how collaborative networks influence the formation and dissemination of knowledge in agricultural water management. The co-authorship and institutional maps provide empirical grounding for theories of knowledge production, demonstrating that innovation emerges from highly interconnected, multidisciplinary, and geographically diverse networks.

Lastly, the integration of soil-water interactions, climate adaptation, and smart irrigation technologies suggests the emergence of a new theoretical paradigm: integrated agro-hydrological sustainability, where soil chemistry, water efficiency, technological automation, and climate resilience converge as inseparable dimensions of agricultural research.

Despite its contributions, this study has limitations that should be acknowledged. The bibliometric analysis relies solely on the Scopus database, which, while comprehensive, may omit relevant research published in local journals or indexed in other platforms such as Web of Science or AGRIS. Consequently, some regionally significant studies may be underrepresented. Second, bibliometric methods capture quantitative trends but cannot fully account for the qualitative depth, contextual nuances, or applied impacts of individual studies. Although the analysis includes visualizations and thematic interpretations, it does not substitute for detailed content analysis of all articles.

Third, the visualization results such as keyword clustering and collaboration networks depend on algorithmic parameters within VOSviewer, which may influence how clusters appear. Small changes in thresholds or weighting could produce slightly different results. Finally, the study does not evaluate the on-the-ground adoption of irrigation technologies or water management practices, which may differ significantly from the trends observed in academic literature. Future research could combine bibliometric insights with field studies or case-based evaluations to provide more holistic policy recommendations.

4. CONCLUSION

This study demonstrates that water management in agriculture has evolved into a complex, multidisciplinary field shaped by environmental pressures, technological innovation, and global sustainability imperatives. Through bibliometric mapping and analysis of influential literature, the research reveals that irrigation efficiency, groundwater conservation, soil salinity management, and sustainable agricultural practices form the intellectual backbone of the field. Earlier research centered on hydrological availability and physical water systems, while contemporary studies increasingly emphasize precision technologies, IoT-enabled irrigation, and climate-resilient farming strategies. This progression reflects a global shift from traditional water management approaches toward integrated and technology-driven solutions capable of addressing emerging climate and resource challenges.

The collaboration networks further indicate that countries such as India, China, and the United States function as major hubs in advancing water management research, supported by strong intercontinental partnerships across Europe, Asia, Africa, and the Middle East. Institutions like ICAR, CSIRO, and ICARDA play pivotal roles in connecting scientific communities and fostering global knowledge exchange. These patterns underscore the importance of coordinated, cross-border efforts in developing scalable innovations and addressing water scarcity, particularly in regions heavily dependent on irrigated agriculture.

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