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Farmer-centered water governance: integrating behavioral and institutional perspectives on farmland water use efficiency

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With increasing water scarcity and climatic uncertainty, enhancing farmland water use efficiency from a farmer-centered perspective has become a critical challenge for sustainable agriculture worldwide. To address this, the present study integrates bibliometric and case-based approaches to provide a comprehensive analysis of the intellectual evolution and empirical validation of farmer-centered WUE research. A total of 1,773 publications retrieved from the Web of Science and Scopus databases (2000–2025) were analyzed using CiteSpace to visualize the structural, thematic, and collaborative evolution of the field. The results reveal a steady expansion in research output, with China, the United States, and India emerging as leading contributors. Thematic clustering and burst analysis indicate a conceptual transition from technology-driven irrigation efficiency toward behavioral and institutional integration, reflecting a paradigm shift toward participatory and adaptive water governance. To complement the bibliometric mapping, case-based validation was conducted across representative regions to interpret how institutional coordination, behavioral heterogeneity, and policy incentives jointly shape farmland WUE. Based on these findings, the study proposes an integrated institutional–behavioral–efficiency framework that links macro-level knowledge evolution with micro-level empirical insights. The results provide both theoretical guidance and practical implications for advancing farmer-oriented water governance and achieving sustainable agricultural transformation.

KEYWORDS

farmland water use efficiency, farmer behavior, case-based analysis, institutional perspectives, adaptive water governance

1 Introduction

Against the backdrop of accelerating global climate change and intensifying water resource constraints, agricultural water resource management is encountering multiple, complex challenges (Vallino et al., 2020). As the largest water-consuming sector worldwide (Yang et al., 2023), agriculture plays a pivotal role in determining the efficiency of water allocation, which in turn has direct implications for food security and ecosystem stability (Canelas and Pereira, 2022). Moreover, efficient water use in agriculture significantly influences the sustainability of rural economies (Garcia et al., 2020) and the effectiveness of environmental governance policies. In this context, improving agricultural water use efficiency (WUE) has become not only a technical objective but also a key component of global strategies for sustainable development and food system resiliency (Brahmanand et al., 2021).

Particularly within irrigation-dominated agricultural systems (Corbari et al., 2024; Zhao et al., 2024), farmland water use efficiency (Aboutorabi et al., 2025) has become a key metric for evaluating both the green transformation of agriculture (Boix-Fayos and de Vente, 2023) and the pursuit of high-quality development under resource constraints.

Currently, agriculture accounts for approximately 60% of total global freshwater withdrawals (FAO, 2024), making it the largest water-consuming sector worldwide. This proportion is even higher in developing regions such as Asia and Africa (Hsiao et al., 2009). Under such pressures, enhancing WUE while ensuring food security has become a core scientific and policy concern, driving an increasing number of interdisciplinary studies at global and regional levels.

Evidence shows that major agricultural economies—including China, India, Pakistan, Iran, and Egypt—face persistent challenges such as low irrigation water-use efficiency, insufficient institutional constraints, and significant heterogeneity in farmer behavior (Monteiro et al., 2024). Within this context, farmers, as key actors in agricultural water use, play a critical role in determining the actual outcomes of water governance policies (Giannoccaro and Berbel, 2011). Their capacity for technological adoption and institutional adaptation largely shapes the effectiveness of such interventions. Thus, the "farmer perspective" has gradually become an essential analytical lens for understanding the fundamental mechanisms underlying variation in efficiency and institutional performance in agricultural water management (O'Keeffe et al., 2018).

Previous studies have explored various pathways to improve agricultural water use efficiency from multiple dimensions, including the evaluation of irrigation technologies (Lankford, 2012), the design of water rights and pricing mechanisms (Mirra et al., 2024), and the optimization of regional water allocation schemes (Dadmand et al., 2020). However, much of this research has focused on macro-level policy frameworks and regional water governance systems, often overlooking the micro-level behavioral unit—the individual farmer (Shahraki et al., 2024). This gap suggests that institutional reforms and technological innovation, while necessary, cannot alone guarantee water-use efficiency unless they are matched with a nuanced understanding of farmers' behavioral logic, cognitive processes, and adaptive capacity (Li et al., 2023).

Many of these studies operate under a linear "policy–technology–performance" assumption, which fails to adequately explain the variability in farmer behaviors and WUE under similar institutional and technological conditions (Medellín-Azuara et al., 2012). Empirically, variations in farmland water use efficiency are primarily driven by micro-level behavioral determinants, including the adoption of water-saving technologies, the understanding and acceptance of water pricing policies, and the degree of institutional adaptability among farmers (Niu et al., 2024; Toan et al., 2015). This reinforces the need to examine WUE through a behaviorally grounded, institutionally contextualized perspective, in which farmers' choices are understood as adaptive responses rather than static outcomes.

In recent years, a growing body of research has begun to examine the behavioral role of farmers in water resource management, drawing upon analytical frameworks from behavioral economics (Alharbi et al., 2025), institutional theory, and related disciplines (Baydur et al., 2023). Studies on farmers' water-saving behaviors have incorporated approaches such as the Theory of Planned Behavior (Badsar et al., 2022), attribution theory, and incentive–response mechanisms (Sok et al., 2020). However, a comprehensive and systematic synthesis of knowledge centered on the "farmer's perspective" remains scarce, particularly one that integrates behavioral, institutional, and technological insights within a unified analytical structure.

To address this gap, the present study systematically examines the intellectual evolution of farmland water use efficiency through a dual-database bibliometric analysis combining records from the Web of Science (WoS) and Scopus databases (Sok et al., 2020; Zhao et al., 2024), ensuring broader disciplinary coverage and methodological robustness. The analysis employs CiteSpace and related visualization tools to map the knowledge structure, thematic evolution, and collaborative networks of global research on water use efficiency from 2000 to 2025.

Beyond quantitative mapping, the study introduces a case-based validation component that complements the bibliometric results with empirical evidence from representative studies across Europe, Asia, the Middle East, and North Africa. This comparative synthesis explores how institutional coordination, behavioral heterogeneity, and cooperative adaptation jointly influence cultivated land water use efficiency (Kassawmar et al., 2024). By bridging bibliometric mapping and case-based interpretation, the research provides a macro-level depiction of intellectual development alongside a micro-level understanding of the behavioral and institutional mechanisms that shape farmer-centered water governance. The principal innovations of this study lie in its integration of multi-source databases, farmer-oriented analytical perspective, and mixed quantitative–qualitative validation framework, which together enrich the interpretative depth of water use efficiency scholarship and connect theoretical insights with real-world agricultural governance practices (Khan et al., 2021).

Despite substantial progress in research on farmland water-use efficiency, existing studies remain fragmented across technical, institutional, and behavioral perspectives, and few attempts have integrated these dimensions within a unified analytical framework. Previous bibliometric studies have primarily focused on macro-level knowledge structures without linking them to farmer decision-making processes, while case-based analyses have seldom been connected to broader disciplinary trends. To bridge these gaps, this study contributes three innovations. First, it develops an integrated institutional–behavioral–efficiency framework that clarifies the interaction mechanisms among farmer incentives, governance arrangements, and water-use outcomes, extending beyond existing models that treat these elements separately. Second, it combines dual-database bibliometric mapping with cross-regional case validation, providing a mixed methodological approach that enables both macro-level pattern identification and micro-level mechanism interpretation. Third, by positioning farmer behavior at the core of WUE research, this study systematically identifies the conceptual and methodological gaps in prior literature and offers a coherent pathway for connecting theoretical insights with practical water-governance interventions.

To address these research gaps, this study integrates bibliometric mapping with five representative empirical cases to systematically examine how institutional arrangements and farmer behaviors jointly shape farmland water use efficiency. By combining global knowledge structures with region-specific evidence, the study develops an integrated institutional–behavioral analytical framework that bridges macro-level research patterns with micro-level irrigation practices. The remainder of the paper is structured as follows: Section 2 presents the data sources and methodological design; Section 3 reports the bibliometric results; Section 4 provides case-based validation; and Section 5 synthesizes the findings to derive policy implications.

2 Methodology and data

This research integrates bibliometric visualization with empirical validation to explore the evolution of cultivated land water use efficiency from the farmer's perspective. By combining large-scale literature mapping with grounded case analysis, the methodology ensures that quantitative insights are aligned with the behavioral and institutional realities of agricultural water management.

2.1 Analytical framework

To link conceptual synthesis with empirical interpretation, an integrated methodological framework was developed (Figure 1). The revised figure combines the data screening procedures and analytical stages into a continuous workflow, providing a clear, transparent structure from data retrieval to final synthesis.

The process begins with selecting the WoS Core Collection and Scopus as the core databases to ensure broad disciplinary coverage across agricultural sciences, environmental studies, water resources, and the social sciences. After database selection, records undergo automated and manual filtering based on thematic relevance, with titles, abstracts, and keywords examined to ensure alignment with farmland water use efficiency from a farmer-centered perspective. Invalid, retracted, or incomplete records are removed, and non-article document types, such as book chapters, editorials, and conference summaries are excluded to maintain bibliometric consistency.

After merging the two datasets and removing duplicates, the remaining valid records form the dataset used for analysis. Bibliometric visualization is then conducted to identify temporal publication trends, thematic clusters, collaboration structures, and emerging research frontiers. These quantitative patterns are further examined through representative empirical cases drawn from regions with diverse governance structures and irrigation systems.

By integrating these components, the analytical framework provides a coherent foundation for interpreting both macro-level intellectual structures and micro-level behavioral mechanisms in farmer-centered water governance.

2.2 Data sources

Bibliometric data were retrieved from the WoS Core Collection and Scopus using a search strategy that combined key terms such as "agricultural water-use efficiency," "irrigation water-use efficiency," "crop water productivity," "farmer behavior," and "farm-level management." The search was restricted to English-language articles and reviews published between 2000 and 2025.

Integrating WoS and Scopus enhances disciplinary breadth and reduces the risks associated with single-database dependence. All retrieved records were exported in standardized formats and prepared for systematic screening. Detailed cleaning procedures, deduplication rules, and final inclusion criteria are described in Section.

2.3 Data screening and workflow transparency

To ensure transparency, reproducibility, and methodological rigor, all retrieved records were processed using a structured data-screening workflow aligned with the core principles of PRISMA but adapted for bibliometric research. Instead of presenting a standalone PRISMA diagram, we integrated the entire screening process directly into the consolidated methodological workflow (Figure 1). This integrated design clarifies how records were identified, filtered, deduplicated, and finalized for analysis while avoiding redundancy.

The initial search retrieved 1,107 records from the WoS Core Collection and 1,452 records from Scopus. After merging the two datasets, automated duplicate detection was performed using title doi author matching rules. Near-duplicate items with inconsistent metadata were further examined manually through abstracts and publication details. Records belonging to non-article document types, including editorials, book chapters, conference summaries, and meeting reports, were excluded to maintain bibliometric consistency.

After automated and manual screening, 1,773 valid publications from 2000 to 2025 were retained. This transparent workflow ensures that the final dataset is comprehensive, thematically consistent, and fully aligned with the analytical objectives of this study.

2.4 Data processing and analytical approach

Following the integrated workflow illustrated in Figure 1, all valid publications were processed and visualized using CiteSpace (version 6.3. R8 Advanced), while Microsoft Excel was employed for descriptive statistics and manual inspection of network structures.

The analytical procedures encompass several dimensions. Annual publication trends reveal the temporal evolution of research activity. Keyword co-occurrence and clustering analyses (LLR/LSI) identify major themes and intellectual structures, while keyword-burst detection highlights emerging frontier topics. Collaboration networks among countries, institutions, and authors are mapped to understand global linkages and patterns of knowledge diffusion. Insights derived from these visualizations are further contextualized through cross-regional case evidence linking institutional arrangements, behavioral mechanisms, and water-use outcomes.

Together, these analytical steps establish a transparent and robust methodological foundation that connects macro-level bibliometric patterns with micro-level farmer behavior and institutional dynamics. The consolidated (Figure 1) provides a straightforward, continuous workflow from data retrieval and screening to bibliometric visualization and case-based interpretation.

This study adopts an integrated institutional behavioral efficiency framework to explain how irrigation governance arrangements influence farmer decision-making and, ultimately, water-use outcomes. Institutions shape the incentives, constraints, and perceived risks faced by farmers, thereby affecting behavioral responses such as

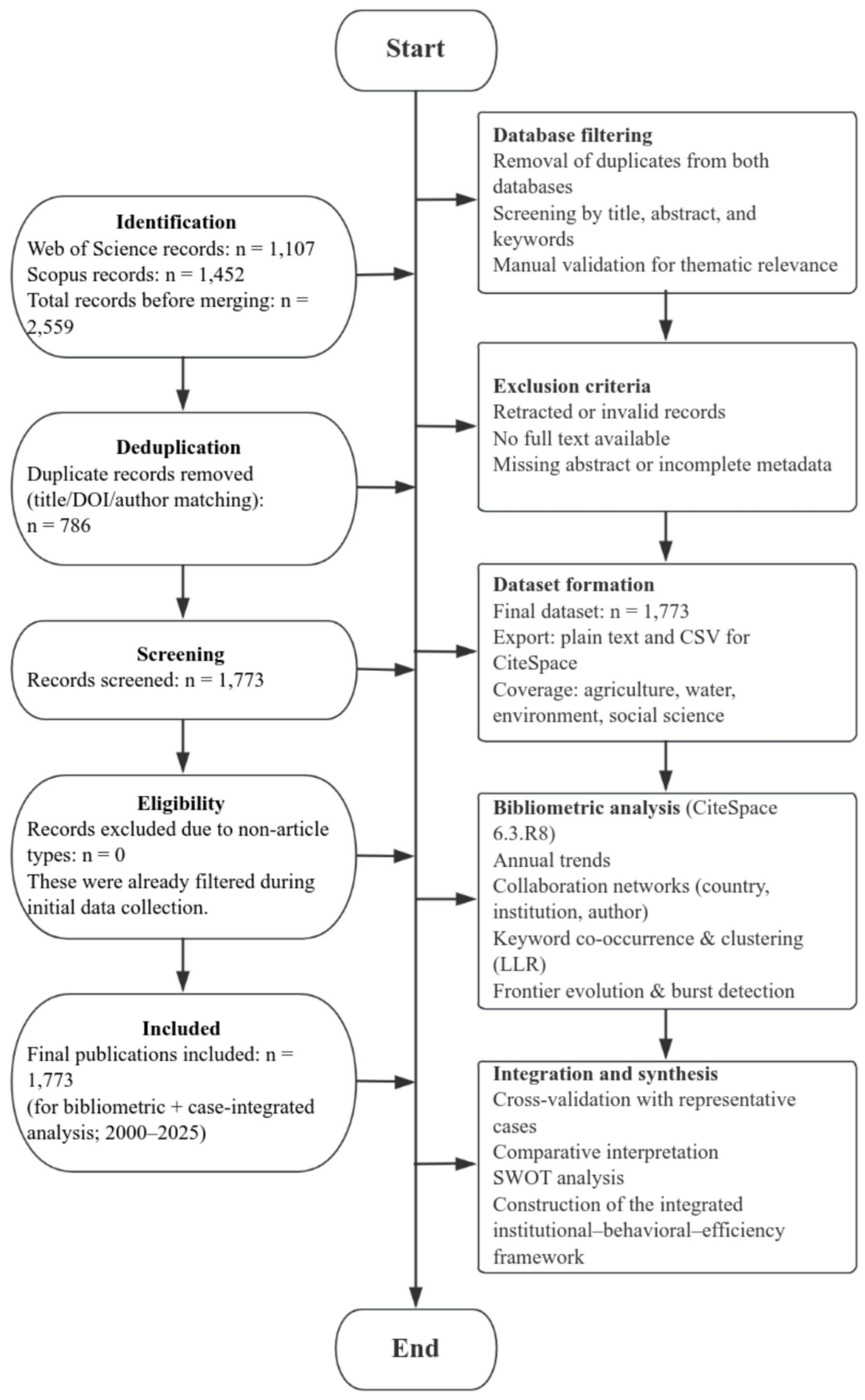

FIGURE 1
Integrated methodological framework and PRISMA-inspired data-screening workflow for farmer-centered farmland water use efficiency research.

irrigation scheduling, technology adoption, and participation in collective action. These behavioral adaptations, in turn, determine the level of farmland water-use efficiency. This causal chain provides the theoretical basis for linking macro-level governance structures with micro-level irrigation practices. It serves as the core analytical lens for interpreting both bibliometric patterns and case-based evidence.

3 Results

Based on a visualized bibliometric analysis of literature from 2000 to 2025 using Citespace (version 6.3. R8 Advanced), this study systematically illustrates the knowledge structure, thematic evolution, collaboration networks, and research frontiers in the field of farmland water-use efficiency from a farmer-centered perspective (Devkota et al., 2013). The integrated dataset—merged from the WoS and Scopus databases after deduplication—encompasses 1,773 valid records, providing a comprehensive and representative foundation for cross-validation.

By constructing knowledge maps of annual publication trends, disciplinary and journal distributions, high-frequency keywords, co-citation and co-authorship networks, and keyword clustering and burst analysis, the study reveals the phased development trajectory and the shifting thematic priorities in global farmer-oriented WUE research. These visual analyses establish the empirical foundation for subsequent case-based validation and policy-oriented discussion (Iqbal et al., 2014).

3.1 Research dynamics and global distribution

The annual publication trend (Figure 2) demonstrates a steady yet nonlinear growth in farmer-centered WUE research between 2000 and 2025. In the early stage (2000–2010), global research output remained sparse, dominated by technical studies addressing irrigation system performance and engineering efficiency (Rodríguez-Díaz et al., 2011). Between 2011 and 2016, an upward shift occurred as agricultural sustainability and climate adaptation became central policy agendas, especially in water-stressed regions such as China, India, Iran, and Spain. After 2017, research activity surged, indicating the maturation of WUE as a cross-disciplinary topic spanning agronomy, environmental economics, and governance studies (Saddique et al., 2025).

Regional analysis shows that China, the United States, and India have become the top contributors, accounting for nearly half of global publications, followed by European countries (Spain, Italy, the United Kingdom) and emerging economies (Iran, Pakistan). This spatial diversification suggests that farmer-oriented water management has shifted from localized irrigation studies to globally coordinated efforts that address shared sustainability goals. The accelerated growth after 2020 also aligns with the intensification of discussions on food–water–climate linkages under the SDGs framework. Such evolution highlights how the scientific community has moved beyond purely technical efficiency metrics toward an integrative understanding of farmer participation, institutional incentives, and adaptive governance.

3.2 Thematic clusters and knowledge structure

The keyword co-occurrence network (Figure 3) illustrates the intellectual organization of the field. High-frequency terms—irrigation, water productivity, efficiency, climate change, and sustainability—form the conceptual backbone, while linkages to governance, farmer behavior, and policy instruments highlight a growing interdisciplinary scope (Lankford, 2012). This interconnected structure reflects the dual emphasis on technical optimization and behavioral adaptation that defines contemporary WUE research (Kang and Eltahir, 2018).

The Log-Likelihood Ratio (LLR) clustering (Figure 4) identifies nine major clusters—water management (#0), climate change (#1), irrigation scheduling (#2), farmer decision-making (#3), conservation agriculture (#4), remote sensing (#5), food security (#6), institutional efficiency (#7), and participatory governance (#8).

Earlier clusters (2000–2010) were dominated by hydrological modeling and efficiency indices, while post-2015 clusters emphasize behavioral and governance aspects, integrating social and economic dimensions into technical evaluation frameworks.

Beyond the descriptive cluster structure, the thematic patterns reveal deeper intellectual drivers behind the evolution of farmer-centered WUE research. Clusters such as "irrigation performance," "water-saving technologies," and "farmer adoption behavior" reflect a shift from engineering-oriented research to a more socio-technical understanding of WUE. The emergence of clusters related to "participatory irrigation management," "risk perception," and

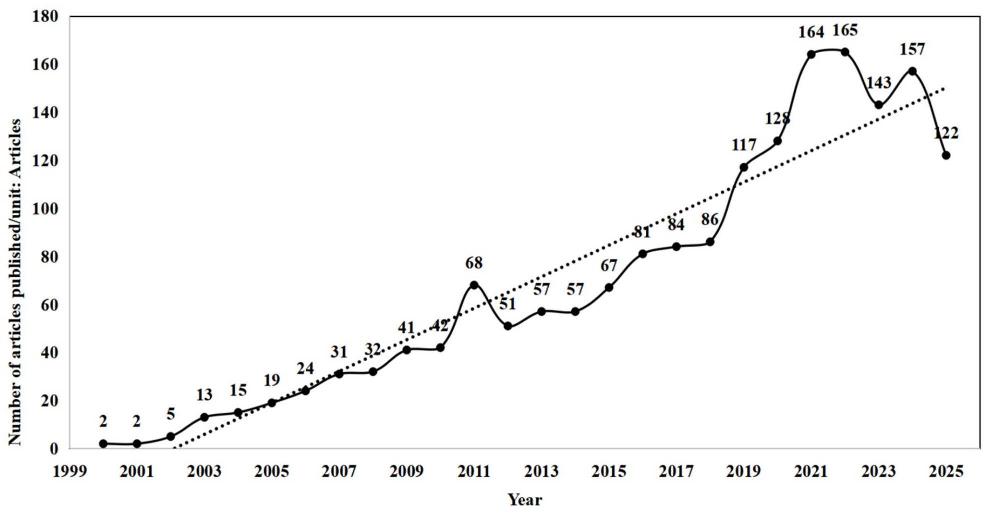

FIGURE 2
Annual publication trend of farmland water use efficiency (WUE) research (2000–2025).

FIGURE 3
Keyword co-occurrence network in farmland water use efficiency research (2000–2025).

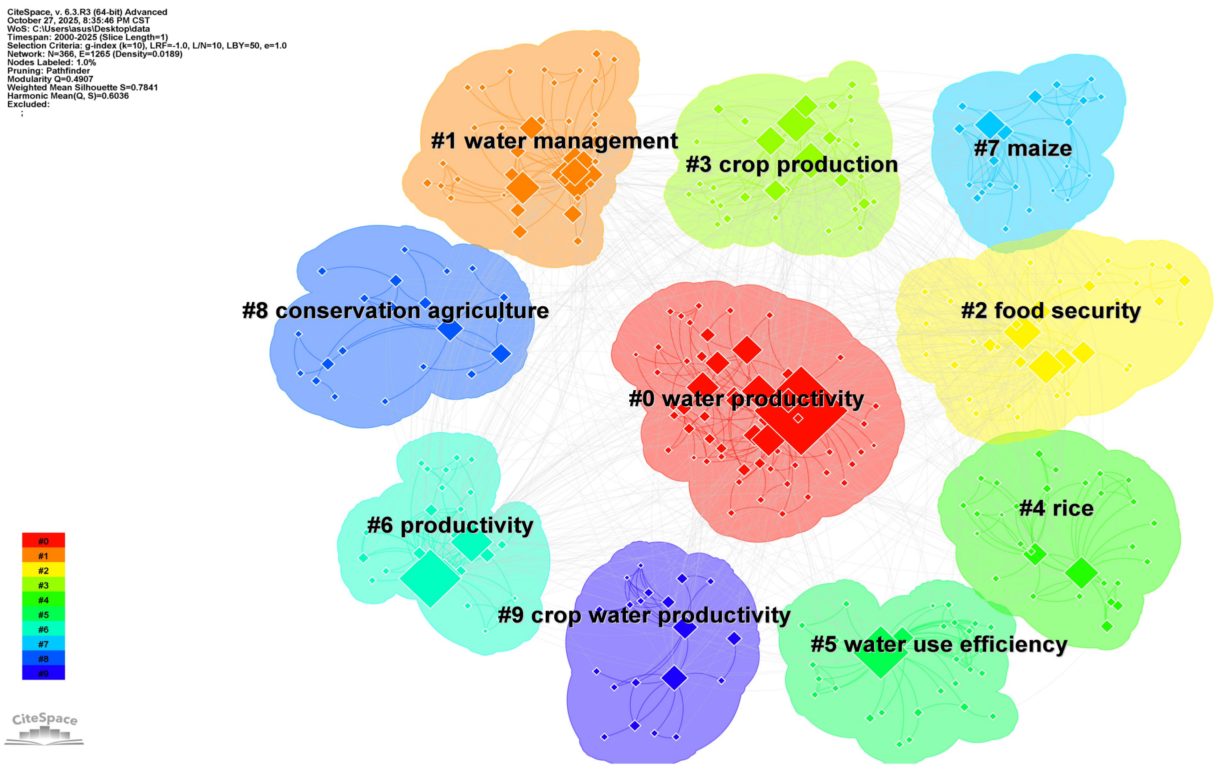

FIGURE 4
Keyword clustering map based on the Log-Likelihood Ratio (LLR) algorithm.

"institutional incentives" indicates that scholars increasingly recognize farmers as active decision-makers rather than passive technology recipients. Compared with earlier bibliometric studies that mainly emphasized hydrological efficiency or remote-sensing evaluation, the present analysis shows a clear shift toward integrating behavioral, institutional, and governance dimensions, underscoring the centrality of the farmer perspective.

3.3 Core journals and knowledge diffusion

The disciplinary and journal distribution (Figure 5) reveals a vibrant, diverse publication ecosystem. Agricultural Water Management remains the core journal, reflecting its enduring focus on irrigation performance, crop–water modeling, and system efficiency. Complementary outlets, such as irrigation and drainage, water resources management, and sustainability, expand the scope beyond hydrological modeling to integrated environmental and socioeconomic evaluation.

In recent years, the Journal of Cleaner Production and Environmental Science and Policy have gained prominence, indicating that WUE research has become a crucial bridge between environmental management and agricultural transformation (Tarkalson et al., 2018).

These core journals not only dominate publication volume but also shape the knowledge landscape of farmer-centered WUE research. Agricultural Water Management and Irrigation and Drainage increasingly publish studies linking irrigation scheduling, water-saving technologies, and farmer behavioral responses, thus bridging engineering research with behavioral and institutional perspectives. Journals such as Agronomy-Basel, Water (Switzerland), and Sustainability extend the discussion to climate adaptation, livelihood resilience, and governance mechanisms. The concentration of farmer-centered WUE studies in these outlets highlights their role as primary platforms integrating institutional, behavioral, and technical insights.

The author collaboration network (Figure 6) mirrors this disciplinary convergence. Prominent scholars—Lankford, Berbel, Humphreys, Jat, and Singh—form central nodes that connect distinct research clusters across Asia, Europe, and North America. These connections illustrate the formation of a global WUE research community characterized by increasing methodological consistency and mutual learning. International collaborations have intensified in the past decade, particularly among research institutions in China, Spain, and Australia, facilitating cross-comparative model calibration and policy testing (Ma et al., 2023).

This diffusion of knowledge across geographical and disciplinary boundaries demonstrates how the WUE field has shifted from fragmented, region-specific studies toward a coordinated international network. The global connectivity revealed here provides the institutional and intellectual infrastructure for the cross-case behavioral analyses presented in Section 4.

3.4 Evolution of research frontiers

The thematic timeline (Figure 7) depicts the sequential evolution of research themes on farmland WUE from 2000 to 2025. Early stage studies (2000–2010) focused on irrigation efficiency, water productivity, and crop yield, reflecting the engineering roots of the discipline. Between 2011 and 2017, attention shifted toward sustainable water management and climate change adaptation, as researchers began integrating hydrological models with policy and social factors. After 2018, new thematic layers began to emerge, including farmer participation, governance flexibility, and data-driven modeling, which collectively indicate a shift from technology-oriented inquiry to an institutional and behavioral synthesis. This temporal evolution demonstrates that the WUE field has broadened conceptually from basic efficiency calculation to a more comprehensive approach centered on adaptive management (Rodríguez-Díaz et al., 2011).

The timezone visualization (Figure 8) complements this analysis by highlighting the temporal intensity and overlap of key research clusters. Keywords such as irrigation scheduling, soil moisture, and remote sensing show high activity density between 2015 and 2020, indicating the consolidation of precision-irrigation technologies. In contrast, governance-oriented terms such as policy reform, farmer perception, and participatory management appear later, with concentrated bursts after 2020. This shift reflects the growing behavioral orientation in WUE research. The chronological layering reveals how scientific attention has progressively moved from

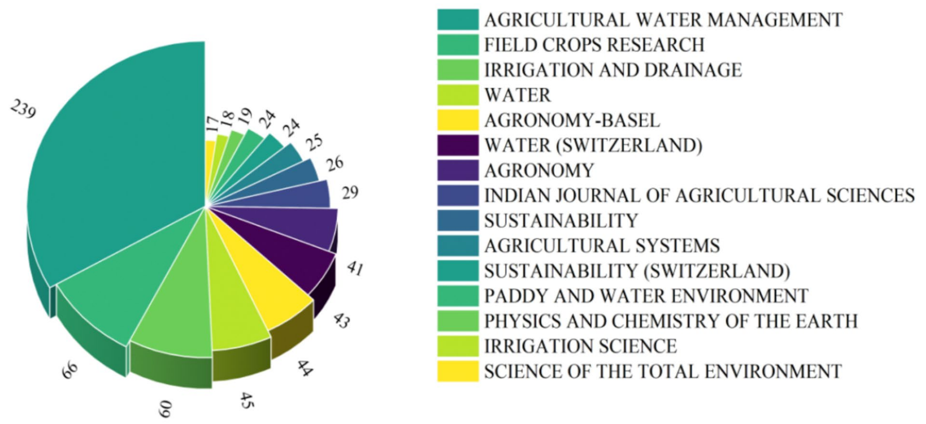

FIGURE 5
Core journals and disciplinary distribution in farmer-centered WUE research.

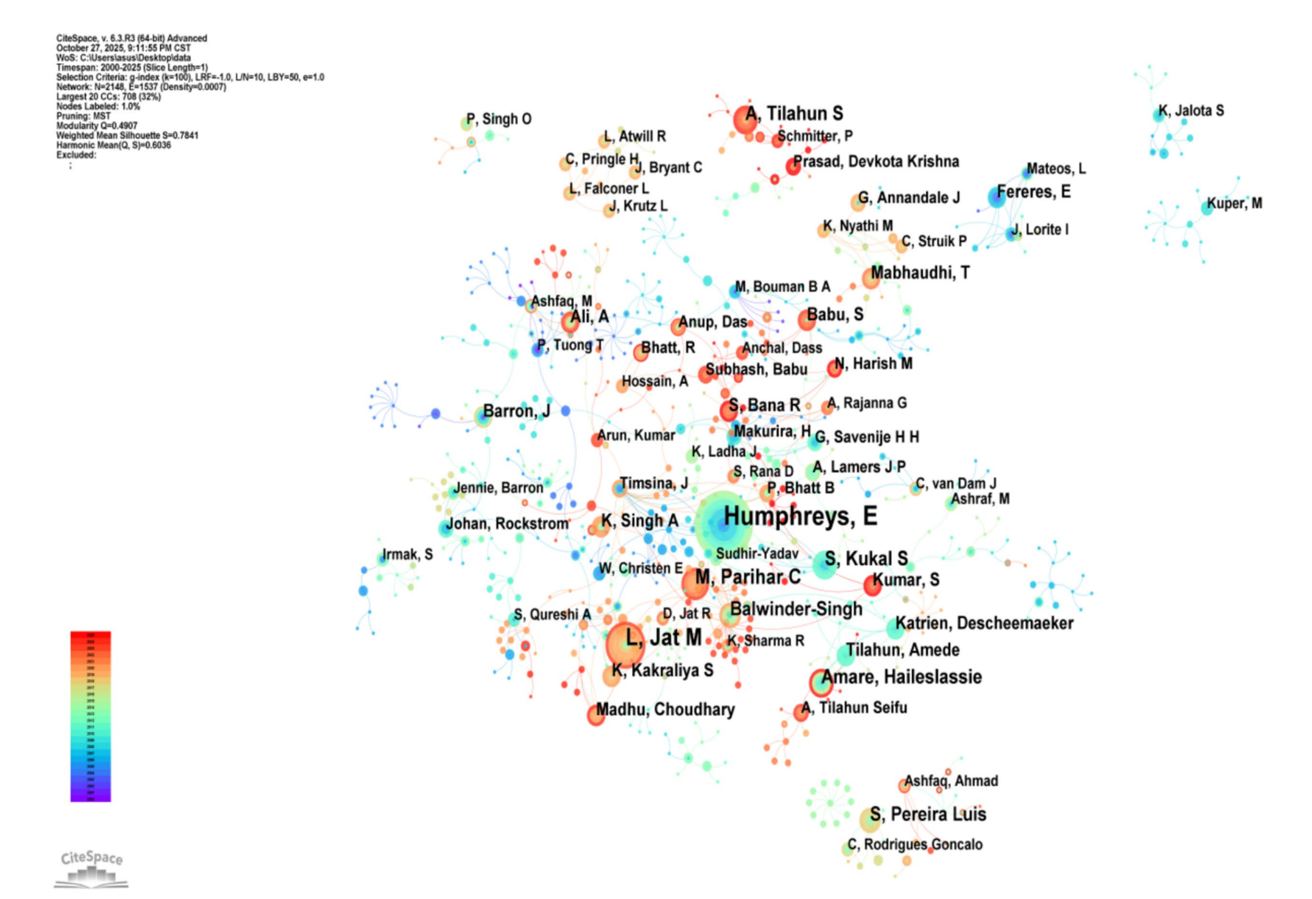

FIGURE 6
Author collaboration network in global farmer-centered WUE research.

technical optimization to social adaptation, aligning with broader global sustainability narratives (Lankford, 2012).

The burst analysis (Figure 9) highlights 25 keywords with the strongest citation bursts, including remote sensing, soil moisture, precision irrigation, food security, and climate-smart agriculture. These keywords reveal the transition toward precision agriculture and digital governance, supported by technological innovations such as GIS, sensors, and machine learning. The persistent use of terms such as participation, policy reform, and irrigation scheduling further indicates the deepening connection between empirical modeling and farmer behavior (Badsar et al., 2022). Such evolving research frontiers signify a paradigm shift in WUE scholarship from quantifying input–output efficiency to interpreting water management as an adaptive social–ecological process.

The burst and timeline analyses further reveal the academic and policy drivers shaping research frontiers. Early bursts related to "irrigation efficiency," "crop productivity," and "water-saving irrigation" reflect a period dominated by technological solutions. Later bursts such as "participatory irrigation management," "climate resilience," "adoption behavior," and "institutional reform" correspond to global shifts emphasizing farmer engagement, decentralized governance, and climate adaptation. Rather than isolated technical trends, these shifts show that the evolution of research frontiers is driven by interactions between farmer behavior, institutional design, and water governance reforms, confirming the growing importance of the farmer perspective.

3.5 Summary of thematic evolution and implications

The integrated visualization of 1,773 studies from WoS and Scopus reveals that farmer-centered WUE research has evolved from a narrow technical niche to a mature interdisciplinary domain.

Three central tendencies can be identified. First, there is a methodological diversification: traditional DEA and SFA models are now complemented by GIS-based monitoring, behavioral simulation, and multi-criteria decision analysis. Second, theoretical convergence is evident, as technical efficiency frameworks are increasingly merged with institutional and behavioral theories, enabling the quantification of social drivers behind water-use outcomes. Third, international collaboration has deepened, creating shared methodological toolkits and encouraging knowledge transfer across continents.

This convergence of perspectives signifies a structural shift in how efficiency is conceptualized, moving from a narrow focus on water productivity to a broader understanding of efficiency as a behavioral outcome shaped by incentives, social networks, and governance design. As a result, the field now offers both empirical and theoretical foundations that support more evidence-based and context-sensitive policy formulation.

As summarized in Table 1, integrating technological innovation, behavioral adaptation, and institutional coordination represents the next frontier of farmer-centered WUE research

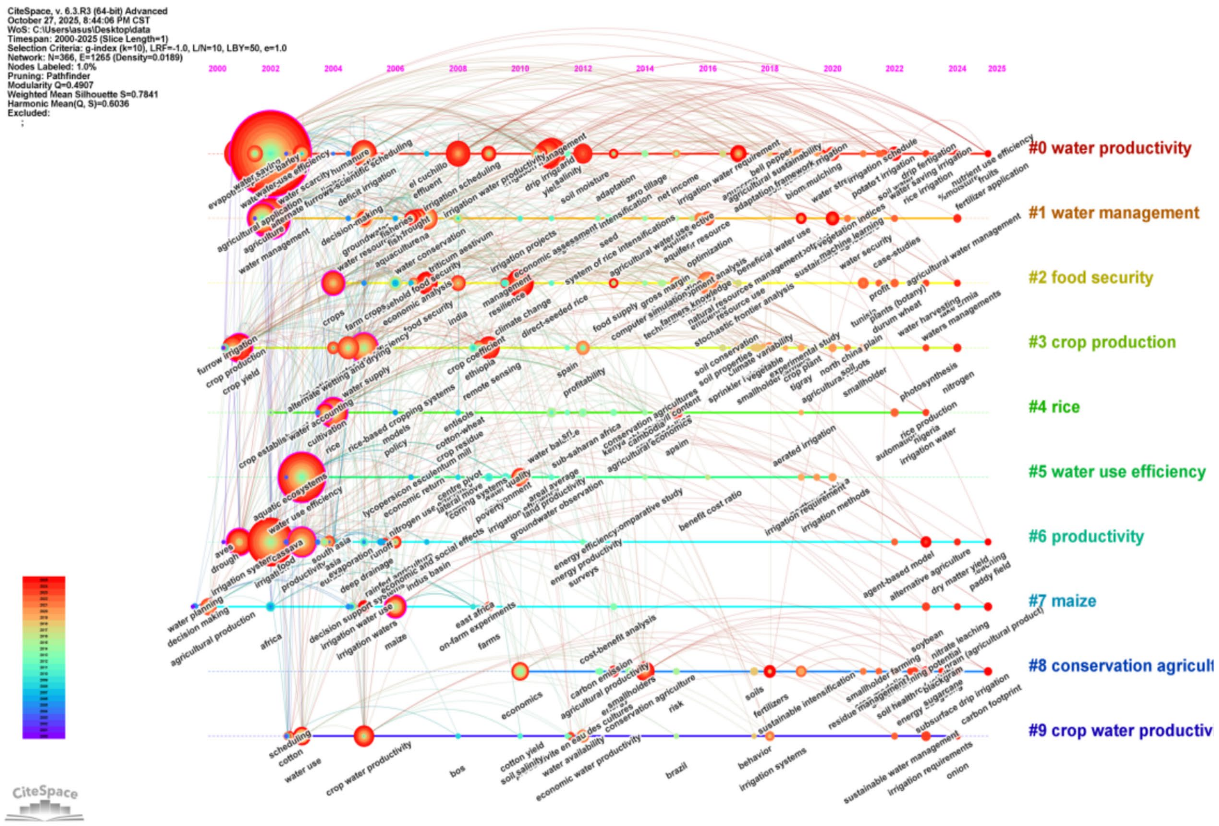

FIGURE 7
Thematic evolution timeline of farmland water use efficiency research (2000–2025).

(Brahmanand et al., 2021). Technological innovation emphasizes the incorporation of remote sensing, IoT-based irrigation, and machine learning into intelligent, automated decision systems; behavioral adaptation focuses on farmer cognition, collective water management, and survey–simulation modeling to design human-centered irrigation strategies; and institutional coordination advances through policy simulation, governance flexibility, and incentive alignment toward climate-resilient institutions for sustainable water use. Together, these three interconnected dimensions outline a holistic research trajectory that moves from isolated technical solutions toward a systemic, adaptive, and participatory paradigm of agricultural water governance.

To ensure a coherent transition from bibliometric patterns to empirical validation, this study links the major clusters identified in Section 3—such as institutional incentives, farmer behavioral decision-making, irrigation governance, and adaptive water-use strategies, to the representative cases presented in Section 4. These clusters collectively reveal the core intellectual themes shaping farmer-centered water governance. The selected cases correspond to these themes by providing empirical illustrations of how institutional arrangements, behavioral heterogeneity, and technological adaptation jointly influence farmland WUE across diverse regional contexts. This bridging paragraph ensures continuity between macro-level knowledge structures and the micro-level mechanisms examined in subsequent case analyses.

4 Case-based insights and validation

To further contextualize the bibliometric findings (Table 2), five representative empirical cases were selected across Europe, Asia, and the Americas to illustrate how farmer behavior, institutional arrangements, and technological adaptation jointly influence cultivated-land WUE. Each case integrates micro-behavioral evidence with policy and governance mechanisms, providing comparative insights into multi-regional practices.

To ensure that the case-based validation reflects diverse institutional, ecological, and socio-economic contexts, the five representative cases were selected according to three criteria. First, each case needed to provide empirical evidence related to farmer-level irrigation behavior, decision-making, or water-use efficiency. This ensured methodological alignment between the bibliometric findings and micro-level behavioral insights. Second, the selection prioritized geographical and institutional diversity, covering Europe, Asia, and the Americas, where irrigation governance structures, policy instruments, and farmer adaptation strategies vary substantially. This cross-regional variation enhances the comparative value of the analysis. Third, preference was given to studies with transparent methodological design and accessible empirical data, supporting analytical consistency across different contexts. Collectively, these criteria ensure that the selected cases are both representative and analytically relevant for validating the integrated institutional–behavioral framework developed in this study.

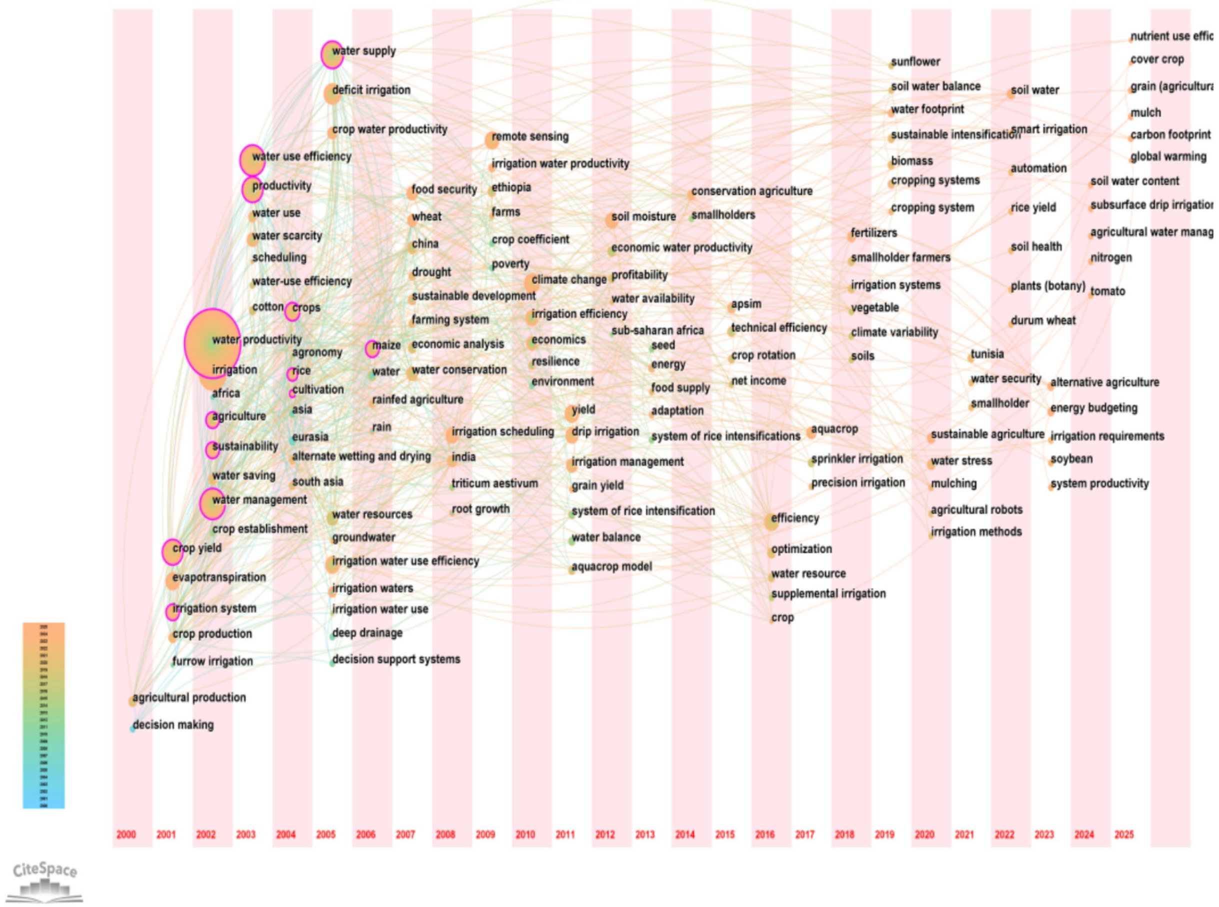

FIGURE 8
Temporal distribution of key research themes in WUE studies.

4.1 Case study 1: socio-psychological motivation in adaptive irrigation

Farmers' psychological and moral motivations often sustain sustainable irrigation behavior beyond economic incentives. In Iran's Central Plateau, Badsar et al. (2022) used Structural Equation Modeling (SEM) to explore how moral norms, perceived risk, and social trust influence irrigation decisions. The results showed that farmers who felt a moral obligation to protect the environment and trusted their local communities were more likely to maintain consistent water-saving practices. These internalized motivations encouraged voluntary adherence to conservation even when financial incentives were minimal.

This case demonstrates that socio-psychological drivers, such as perceived responsibility, moral obligation, and collective trust, are critical behavioral mechanisms sustaining WUE. Policies that rely solely on subsidies or technical training may not achieve lasting change unless they also cultivate environmental ethics and community cohesion. Incorporating moral education, peer learning, and participatory awareness programs into irrigation initiatives can strengthen farmers' intrinsic commitment to conservation and enhance long-term behavioral stability.

This case highlights that fostering moral responsibility and social trust can transform water-saving irrigation from an external mandate into a self-sustaining behavioral norm.

4.2 Case study 2: farmers' behavioral responses to drought stress and groundwater management policies

In regions under increasing climate pressure, farmers' adaptive decisions directly influence irrigation outcomes. Hou and Zhou (2023) investigated maize farmers in China's Huang Huai Hai Plain using a random-effects model and found that irrigation frequency and timing were driven by rational assessment of yield sensitivity and water costs. Farmers prioritized irrigation during critical growth stages, such as tasseling and milk ripening, to maximize returns under drought stress. This adaptive scheduling reflects dynamic decision-making that balances resource constraints with production goals.

At the same time, behavioral adaptation depends heavily on institutional communication and perceptions of policy. Farmers with a better understanding of local water-pricing and drought-compensation mechanisms demonstrated greater flexibility in managing irrigation schedules. Conversely, those unaware of policy

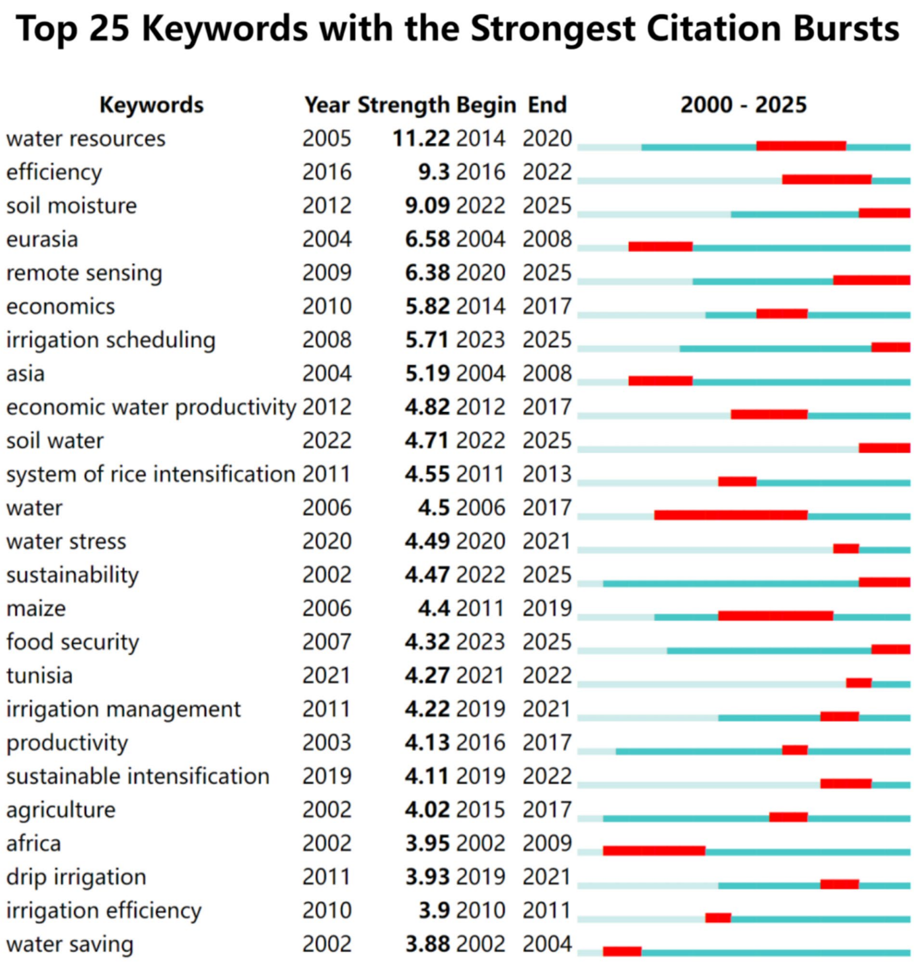

FIGURE 9
Top 25 keywords with the strongest citation bursts (2000–2025).

TABLE 1 Research trends and future directions.

Research dimension	Emerging themes	Methodological trends	Future direction
Technological innovation	Remote sensing, IoT-based irrigation, machine learning	Integration of data-driven models and hydrological simulation	Intelligent, automated irrigation decision systems
Behavioral adaptation	Farmer cognition, collective water management, behavioral heterogeneity	Mixed-method behavioral modeling, survey–simulation linkage	Human-centered precision irrigation strategies
Institutional coordination	Water rights reform, governance flexibility, incentive alignment	Policy simulation, cross-scalar governance modeling	Adaptive institutions for climate-resilient water use

instruments tended to irrigate reactively, reflecting weaker adaptive capacity. Beyond China, evidence from California groundwater governance system reinforces the importance of policy trust. Niles and Hammond Wagner (2019) found that farmers' compliance with groundwater regulation was strongly associated with perceived fairness and transparency of policy processes. When farmers trusted institutions, voluntary participation replaced coercive enforcement, yielding more sustainable irrigation outcomes.

This case demonstrates that adaptive irrigation behavior emerges from rational risk management supported by effective policy communication and institutional trust.

4.3 Case study 3: institutional incentives and cooperative governance for equity in adaptive irrigation systems

Institutional design that aligns economic incentives with participatory governance can simultaneously improve efficiency and fairness in irrigation systems. In southern Spain, Giannoccaro and Berbel (2011) examined the effects of the Common Agricultural Policy (CAP) on irrigation behavior and found that linking water-use quotas with market-based pricing improved WUE by 15 to 20%. Farmers became more responsive to signals of water scarcity when

TABLE 2 Comparative empirical cases of farmer-level water use efficiency.

Focus dimension	Region/country	Core approach	Main findings	Policy/behavioral implication	Reference
Socio-psychological motivation in adaptive irrigation	Central Plateau, Iran	Structural Equation Modeling (SEM)	Moral obligation and social trust improved the consistency of sustainable irrigation.	Integrating social and moral norms strengthens behavioral sustainability.	Badsar et al. (2022)
Farmers' behavioral responses to drought stress and groundwater management policies	Huang–Huai–Hai Plain, China	Survey with random-effects model and marginal analysis	Farmers irrigated at key growth stages when marginal benefits outweighed costs.	Adaptive behavior reflects rational decision-making under risk and price dynamics.	Hou and Zhou (2023)
	California, USA	Questionnaire + Logit regression	Trust and perceived policy fairness shaped farmers' support for governance.	Building social trust enhances policy acceptance and participation.	Niles and Hammond Wagner (2019)
Institutional incentives and cooperative governance for equity in adaptive irrigation systems	Southern Spain (Andalusia)	Econometric modeling integrating environmental and behavioral data	Market-based quota coordination improved WUE by 15–20% under CAP reforms.	Institutional pricing mechanisms can align farmer incentives with water-saving outcomes.	Giannoccaro and Berbel (2011)
	Southern United States	Logit regression and comparative analysis	Participatory management improved fairness and irrigation efficiency by ~20%.	Farmer cooperation and participatory governance enhance collective resource use.	Adusumilli and Wang (2019)

economic rewards were clearly tied to conservation performance. This coherence between agricultural subsidies and water pricing encouraged adaptive irrigation without compromising yields.

Similar institutional success has been observed in the southern United States. Adusumilli and Wang (2019) reported that participatory water-user associations increased irrigation efficiency by about 20% through cooperative decision-making and transparent monitoring. Farmers who were members of these associations were more likely to adopt efficient technologies and comply with allocation rules. The combination of market incentives and collaborative governance provides a dual pathway to institutional success: economic instruments create motivation, while participatory structures sustain collective accountability. Embedding farmers within transparent governance systems thus converts fragmented irrigation practices into coordinated, equitable, and resilient management frameworks.

This case illustrates that coherent policy design coupled with cooperative governance strengthens both efficiency and equity in achieving sustainable WUE.

4.4 SWOT analysis of farmer-level water-use efficiency practices

By synthesizing the five empirical cases, a SWOT framework was developed to summarize the internal and external factors that shape farmer-level WUE. The strengths mainly stem from growing institutional coordination that links agricultural policy with resource management, as seen in Spain's CAP-based incentive mechanisms and China's adaptive irrigation programs. These arrangements provide structural support for farmers' behavioral adjustment and promote the diffusion of efficient irrigation technologies. The weaknesses, however, lie in fragmented governance and inconsistent policy enforcement, especially in regions where water rights are poorly defined or subsidies lack stability. Limited access to technical knowledge and monitoring systems further restricts smallholders' ability to sustain efficiency improvements over time.

In terms of opportunities, technological innovations (e.g., precision irrigation, digital water accounting) and participatory governance models present new pathways for integrating behavioral and institutional approaches. Strengthening farmer training, peer learning, and trust-based extension services can amplify these positive dynamics. Conversely, threats emerge from climatic uncertainty, policy volatility, and socioeconomic inequality. Water scarcity pressures and competing land uses may widen the gap between large and small farmers, undermining collective water governance. To counter these risks, adaptive governance should combine financial incentives with moral and social drivers, ensuring that efficiency gains are both equitable and resilient across different farming systems.

Taken together, the five representative cases provide empirical support for the proposed institutional-behavioral-efficiency framework. Contexts characterized by clear, coherent, and incentive-compatible institutional arrangements tend to elicit more proactive farmer behaviors, including timely irrigation, the adoption of water-saving technologies, and participation in collective management, all of which are associated with higher irrigation efficiency. By contrast, cases marked by institutional ambiguity, weak enforcement, or misaligned incentives show limited behavioral adaptation and relatively low efficiency. These cross-case patterns confirm the central proposition of the framework, namely that institutions shape farmer behaviors, and that behaviors act as the proximate drivers of water-use efficiency outcomes (Figure 10).

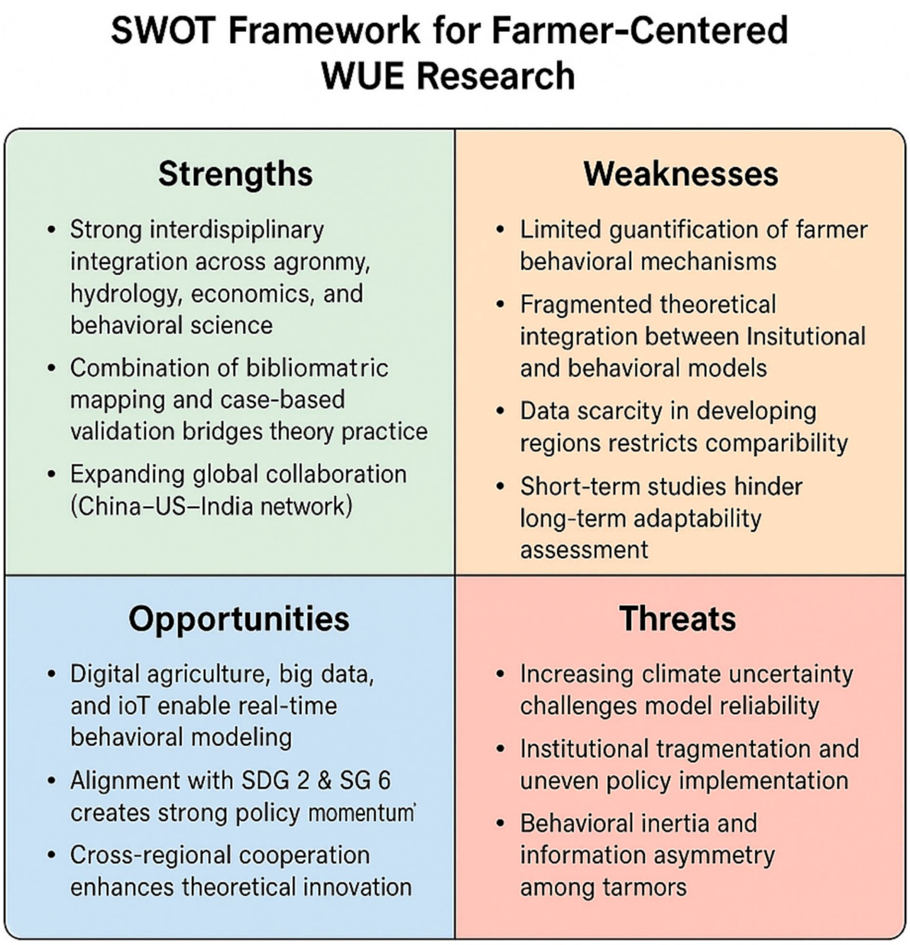

FIGURE 10
SWOT framework summarizing the internal and external conditions of farmer-centered farmland water use efficiency research. The framework identifies four dimensions—strengths, weaknesses, opportunities, and threats—reflecting the interdisciplinary integration, methodological gaps, external policy drivers (including SDG 2: Zero Hunger and SDG 6: Clean Water and Sanitation), and environmental or institutional risks influencing the development of this research field.

Across these five cases, several common insights emerge. Institutional coordination converts technical potential into practical adoption; behavioral motivation sustains long-term engagement; and cooperative governance builds the social foundations for equitable and resilient outcomes. Collectively, these findings reaffirm that improving WUE is not merely a matter of technological innovation. However, an evolving process of adaptive governance is anchored in farmer behavior, institutional trust, and shared learning.

4.5 Cross-regional comparative synthesis

To ensure analytical consistency across the five cases, a unified comparative framework was applied focusing on three dimensions: behavioral drivers, institutional incentives, and efficiency outcomes. Outcomes. These dimensions correspond directly to the institutional-behavioral-efficiency framework developed in Section 2 and enable systematic comparison across heterogeneous regional contexts.

Across all cases, farmers' behavioral responses emerged as a critical determinant of irrigation performance. However, the dominant behavioral mechanisms varied across contexts. In areas with strong market signals or clear economic incentives, farmers adjusted water use based on cost–benefit considerations, whereas in regions with low price sensitivity, social norms and risk perceptions played a more influential role. This variation highlights the different pathways through which behavioral heterogeneity shapes water-use decisions.

Institutional arrangements also exhibited clear regional differentiation. Cases characterized by decentralized water-user associations demonstrated higher levels of compliance, monitoring, and collective action, while regions relying on top-down administrative allocation experienced weaker participation and lower adoption of water-saving practices. These differences suggest that institutional adaptability significantly influences the alignment between farmer incentives and water-use efficiency.

Despite regional variations, a shared pattern is evident: behavioral mechanisms, institutional design, and water-use efficiency are interdependent rather than isolated factors. The cross-case comparison reveals that policy interventions are most effective when economic incentives, governance flexibility, and behavioral drivers reinforce each other, forming coherent institutional-behavioral pathways. These synthesized insights provide a macro-level perspective that connects case-specific findings to broader implications for farmer-centered water governance.

5 Discussion

By integrating bibliometric data from both the WoS and Scopus databases after rigorous deduplication, this study achieves comprehensive coverage and minimizes potential bias arising from single-source analyses. Moreover, the inclusion of cross-regional case-based validation enhances the interpretive robustness by linking global research patterns with localized empirical realities.

The institutional, behavioral, and efficiency framework proposed in this study differs fundamentally from earlier conceptual models that addressed these elements separately. While previous approaches often focused on technological determinism or institutional design alone, the present framework explicitly captures the dynamic interactions between governance structures, farmer decision making, and water-use performance. This integrated perspective enables a more comprehensive understanding of how incentives, norms, and constraints shape on-farm water-use outcomes. In addition, the mixed methodology that combines bibliometric trend analysis with cross-regional case validation provides an empirical depth that neither macro-level mapping nor individual case studies can achieve on their own. This combined approach offers a clearer pathway for translating disciplinary knowledge into more effective and farmer-centered water-governance strategies.

The findings of this study demonstrate that farmland water use efficiency (WUE) research has evolved from a technology-driven inquiry toward a behavioral and institutional synthesis, reflecting an increasing recognition of farmer participation and policy coordination. This multidimensional shift underscores the growing emphasis on behavioral adaptation, institutional flexibility, and participatory governance as the key drivers of sustainable water management. The integration of bibliometric mapping with case-based evidence thus provides a solid empirical foundation for understanding how these dynamics interact across different spatial and institutional contexts.

5.1 Institutional adaptability and governance flexibility

Empirical evidence confirms that institutional design and coordination mechanisms are foundational determinants of water-use performance. Across different socio-ecological contexts, including Spain's irrigation quota systems and Morocco's participatory water governance, improvements in WUE are driven by institutional frameworks that are adaptive and incentive compatible. These frameworks translate technical guidelines into actionable rules by aligning farmer interests with broader sustainability objectives (Kernecker et al., 2021).

At a broader scale, flexible governance enables local experimentation and learning from feedback, with policies continuously refined in response to environmental and socio-economic conditions. This adaptive governance logic marks a shift from static regulation to dynamic coordination (Oliver and Strager, 2021). Rather than prescribing fixed standards, institutions now operate as evolving systems that encourage collaboration among farmers, irrigation associations, and policy agencies (Reimer et al., 2013). Such adaptability not only improves implementation efficiency but also mitigates risks of behavioral non-compliance by fostering shared ownership of water resources (Peng et al., 2022).

5.2 Behavioral heterogeneity and farmer decision dynamics

The analysis also highlights that farmers' behaviors, shaped by cognitive diversity, social interactions, and subjective risk assessments, constitute the most decisive factor in realizing institutional objectives. Differences in education, experience, and access to information lead to varied interpretations of policy incentives and technological guidance. Farmers' decision making is therefore embedded in both economic rationality and socio-psychological processes (van Dijk et al., 2022).

Furthermore, behavioral responses are influenced by community-based learning and peer effects, which amplify or constrain the diffusion of technology (Khan et al., 2025). When farmers observe the benefits of water-saving practices among peers, adoption rates increase through imitation and shared trust. Conversely, in environments lacking information transparency, risk aversion and social inertia can hinder innovation (Hu et al., 2025). Recognizing this behavioral heterogeneity requires policymakers to shift from uniform incentive systems to differentiated, context-sensitive approaches that address the diversity of farmer motivations and capabilities. In doing so, agricultural water governance transitions from control-based to learning-oriented models, emphasizing empowerment and adaptive participation (Matinju et al., 2023).

5.3 From empirical complexity to modeling integration

Recent advancements in data analytics and modeling provide new tools for interpreting the complex interactions between institutions and behavior. The evolution from static evaluation to dynamic modeling represents a paradigm shift in WUE research, in which traditional efficiency indices are increasingly complemented by multi-agent simulations, structural equation models, and remote sensing integration (Ma et al., 2025). These hybrid approaches enable the quantitative representation of behavioral variability and feedback loops across different governance levels.

Through such methodological convergence, research is moving closer to capturing real-world complexity. Digital technologies and modeling systems now allow for scenario-based planning that incorporates uncertainty, behavioral adaptation, and spatial heterogeneity (Filintas et al., 2022). By integrating behavioral data into predictive models, scholars and policymakers can better forecast irrigation outcomes under varying institutional and climatic conditions. This integration not only bridges disciplinary divides but also supports more evidence-based policy experimentation and farmer-oriented decision support systems.

5.4 Policy implications and future perspectives

The insights derived from both bibliometric and case-based analyses converge on several key policy implications. First, institutional flexibility should be strengthened to accommodate local adaptation, enabling responsive adjustment of water allocation and pricing mechanisms (Giannoccaro and Berbel, 2011). Second, behavioral dimensions must be explicitly incorporated into policy design, acknowledging that efficiency outcomes depend on farmers' perceptions, trust, and social learning processes (Gholamrezai et al., 2021). Third, advancing methodological integration by combining digital technologies with participatory governance can enhance both transparency and accountability in water management systems.

Looking forward, future research should focus on bridging behavioral science and water governance through longitudinal and cross-regional studies. This direction would enable the identification of universal behavioral drivers and contextual factors influencing WUE performance (Da Silveira et al., 2025). Moreover, establishing participatory monitoring systems in which farmers contribute real-time behavioral and environmental data can further strengthen adaptive governance. Ultimately, achieving sustainable cultivated land water use efficiency requires not only technological innovation but also an evolving governance architecture capable of learning from behavioral diversity and institutional feedback (Mubako et al., 2018).

To further clarify the practical value of the proposed institutional–behavioral–efficiency framework, this study highlights that the integration of incentive structures, behavioral responses, and efficiency outcomes can directly inform the design of farmer-participatory governance strategies. By identifying how institutional flexibility and behavioral heterogeneity jointly shape water-use outcomes, the framework provides a diagnostic tool for policymakers to tailor irrigation rules, water-pricing mechanisms, and participatory platforms to different farmer groups. This contributes to more adaptive, inclusive, and behavior-responsive water-governance arrangements.

6 Conclusion

The present study provides a comprehensive mapping of research on cultivated land WUE from the farmer's perspective by integrating bibliometric analysis with case-based validation. By combining CiteSpace visualization with empirical evidence, it identifies the intellectual trajectory, thematic evolution, and institutional–behavioral mechanisms that define this emerging field. The findings highlight that improving WUE is no longer a purely technical challenge but rather a complex socio-institutional process that requires coordination among multiple actors, adaptive governance, and behavioral engagement.

The bibliometric analysis reveals that global research on cultivated land WUE has undergone a clear evolution from technological optimization toward behavioral and institutional integration. Early studies focused primarily on irrigation efficiency and engineering interventions, while recent work emphasizes social learning, incentive alignment, and participatory management. This transition reflects the growing recognition that sustainable water management depends on how effectively institutions interact with the decision-making logic of farmers.

The case-based evidence further validates this paradigm shift. Across different agro-ecological contexts, institutional adaptability, behavioral diversity, and methodological innovation jointly determine WUE outcomes. The Spanish and Moroccan experiences illustrate how institutional flexibility and cooperative governance enhance the efficiency of irrigation systems. The Chinese cases demonstrate that farmer heterogeneity and social networks significantly shape behavioral responses and technology adoption. The Iranian example shows the potential of behavioral modeling and simulation to anticipate complex adaptation dynamics. Together, these cases confirm that the pathways to efficiency are embedded in both formal rules and informal behavioral processes.

Looking ahead, the pursuit of higher WUE requires a dual focus on governance adaptability and behavioral responsiveness. Policymakers should move beyond uniform interventions toward context-sensitive strategies that empower local actors, incorporate behavioral insights, and promote cross-scale coordination. Meanwhile, future research should deepen methodological integration by combining field surveys, behavioral modeling, and remote-sensing analytics to generate more dynamic and predictive insights. Ultimately, sustainable water use in cultivated lands will depend on an iterative process of institutional learning, technological co-innovation, and the active participation of farmers in co-managing scarce water resources.

Data availability statement

Publicly available datasets were analyzed in this study. The bibliometric data analyzed in this study were obtained from publicly available databases: the Web of Science Core Collection (Clarivate Analytics) and Scopus (Elsevier). Access to these databases requires institutional or individual subscription. The search strategies, time span (2000–2025), document types (articles and reviews), and filtering criteria are fully documented in the Methods section to ensure transparency and reproducibility.

Author contributions

XL: Project administration, Writing – original draft, Supervision, Writing – review & editing. YaL: Methodology, Conceptualization, Writing – original draft, Writing – review & editing. YW: Writing – review & editing, Software. ZM: Writing – review & editing, Formal analysis. YiL: Writing – review & editing, Investigation. KL: Writing – review & editing, Project administration. LL: Resources, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work 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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