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A systematic literature review on adoption and impact of micro-irrigation

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ABSTRACT

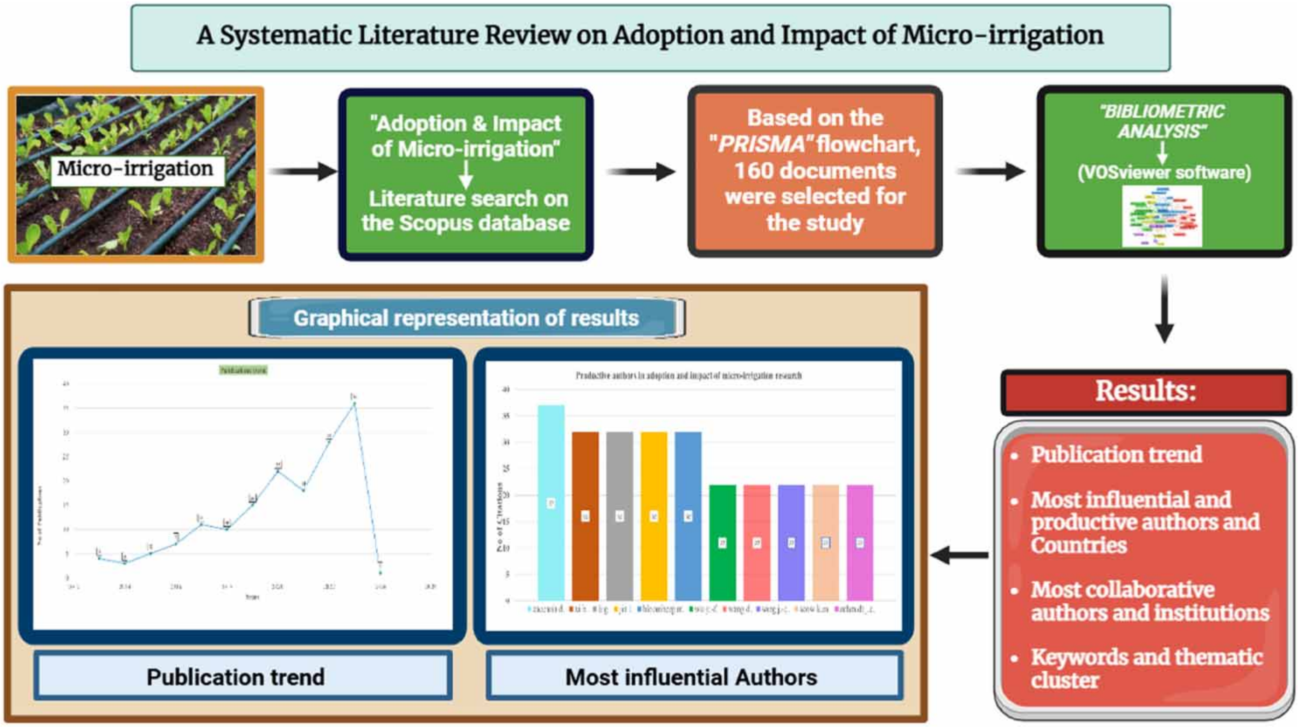
Water is an indispensable resource, and it is crucial for sustaining human life and agriculture. Nowadays, the share of water for agriculture is also shrinking. In the agricultural sector, micro-irrigation (MI) has emerged as a prominent technology for the efficient utilization of available water. However, understanding the adoption and impact of this technology is essential for its success. While existing studies on MI technologies were often limited to specific locations, this study addressed this gap by analysing 160 documents from the Scopus database through a systematic literature review and bibliometric analysis with thematic clustering. The study examined influential authors and nations, keyword co-occurrences, co-citations, and collaborations among authors and institutions. VOSviewer was utilized for bibliometric analysis. The research trend showed a steady increase in MI studies, with Zaccaria D. being the most productive author and the United States being the most influential country with several publications. *Agricultural Water Management* emerged as the most impactful journal, with Coelho E.F. being the most cited author. Additionally, three thematic clusters, namely effects of irrigation water, weed growth and crop yield, and irrigation and organic cultivation, were identified and discussed.

Key words: adoption, bibliometric analysis, co-citation analysis, impact, micro-irrigation

HIGHLIGHTS

- This paper examines the publication pattern of adoption and impact of micro-irrigation research.
- This paper also examines the most productive and influential authors, countries, and collaborative authors and institutions in the adoption and impact of micro-irrigation research.
- This study helps to assess the efficacy of micro-irrigation systems in improving crop yield and saving energy, labour and the environment when compared to conventional methods of irrigation.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water stands as a vital natural resource essential for supporting human life on earth. However, its availability is dwindling globally. Khalid *et al.* (2018) suggested that by 2025, 60% of the world's population will confront severe water scarcity. The agricultural sector faces severe jeopardy from climate change, posing substantial risks to both developed and developing countries (Field & Barros 2014). Climate change worsens the situation by intensifying floods and droughts, altering precipitation patterns, adjusting water resources, and accelerating glacier melt, thereby contributing to the elevation of sea level (Aqueduct 2024). More than 85% of the original natural wetland area was depleted, of which 75% of the land surface underwent substantial modifications, thereby diminishing the capacity of Earth's ecosystems to manage water resources sustainably (Díaz *et al.* 2019). In the sphere of water consumption, agriculture currently utilizes 87% of the world's consumptive water resources (Villalobos & Fereres 2016), with approximately 30% sourced from unsustainable outlets (Liu *et al.* 2017). Agricultural water consumption stands as the primary global user of water, profoundly influenced by climate change, socio-economic progress, and population expansion (Ward & Pulido-Velazquez 2008; Gerten *et al.* 2020). Roughly 40% of croplands worldwide encountered water scarcity previously, with projections indicating a worsening scenario in the future (Liu *et al.* 2022). The exacerbation of agricultural water scarcity has the potential to impact food production, posing a threat to food security, especially for impoverished populations (Tong & Elimelech 2016; Pastor *et al.* 2019).

Enhancing water efficiency within the agricultural sector emerged as a pivotal objective for preserving water resources and mitigating water scarcity (Yazdanpanah *et al.* 2014; Yazdanpanah *et al.* 2015; Azadi *et al.* 2019; Rahimi-Feyzabad *et al.* 2020). The imminent global challenge of water hazards demands immediate attention. To confront these challenges, farmers can adopt water saving technologies, specifically micro-irrigation (MI) methods such as drip irrigation, sprinkler irrigation, and subsurface drip irrigation (SDI). Srivastava *et al.* (2010) noted that irrigation efficiency could be enhanced to 95% through the transition from conventional irrigation methods like border or furrow irrigation (FI) to pressurized irrigation systems. Furthermore, the availability of water for irrigation was diminishing steadily, while the expenses associated with creating water sources continued to rise. Bhaskar *et al.* (2005) emphasized the necessity for advanced irrigation technologies because the productivity of irrigated land and the efficiency per unit of water remained suboptimal compared to their potential.

The MI system plays a significant role not only in conserving water but also in effectively managing energy, labour, and fertilizer resources to enhance crop production. It contributed to uniform water application and water use efficiency, eliminated the need for land levelling, ensured consistent irrigation for agricultural fields, enhanced cropping intensity, optimized irrigation water usage, and uplifted the socio-economic status of farmers. Apart from improving water use efficiency, MI offered additional economic and social advantages. Empirical evidence demonstrated that MI boosted productivity across various crops, reduced weed growth, mitigated soil erosion, and reduced cultivation expenses, particularly labour-intensive weeding, as well as reduced electricity consumption (Grewal *et al.* 2021). Results from a field experiment suggested that drip irrigation is predominantly used as a water-saving technique in the cultivation of both field and greenhouse crops (LÜ *et al.* 2015). Micro-sprinkler irrigation is a modern irrigation technology designed for water conservation and was developed relatively recently. In contrast to drip irrigation, its manufacturing costs were lower because it did not require labyrinth channel emitters (Zhang *et al.* 2020).

Despite the availability of various water-saving technologies, the adoption of these technologies ultimately relies on individual farmers. Embracing water-saving technologies such as MI methods like drip, sprinkler, subsurface drip, and micro-sprinkler irrigation systems has the potential to alleviate the global water crisis in agriculture. Certain non-OECD countries exhibited higher rates of drip irrigation adoption. For instance, in Israel, more than 50% of the irrigated land was under the use of drip irrigation (OECD 2011). Similarly, in Jordan and Cyprus, adoption rates were approximately 60 and 95%, respectively (Alcon *et al.* 2011). In literature, the discussions surrounding the effects of MI technologies typically emphasized their advocacy for three primary objectives: conserving water in irrigated agriculture to mitigate water scarcity, using them as a strategy to increase income and reduce poverty in rural areas, and enhancing food and nutritional security for rural households (Bilgi 1999; Shah & Keller 2002; Narayanamoorthy 2003; Upadhyay 2003).

Therefore, examining the adoption and impact of MI technologies in agriculture was crucial. Given the gap in existing research, the study aimed to examine the specific trends in the adoption and impact of MI research. Additionally, there was a lack of research in this domain that incorporated trend analysis and identified the most prolific and influential authors, as well as the countries involved in the research. Furthermore, there were no studies examining citation analysis, co-occurrence analysis, co-authorship analysis, and bibliometric analysis concerned with the adoption and impact of MI. To fill these gaps, a systematic literature review approach was employed to assess the existing literature on the adoption and impact of MI.

The current study also provided a literature assessment through bibliometric analysis to address various research inquiries. The following are the prominent research questions:

1. What was the research trend in the adoption and impact of MI research?
2. Which authors and countries were the most productive and influential in the adoption and impact of MI research?
3. Who were the most collaborative authors and institutions in the adoption and impact of MI research?
4. What were the most recurrent keywords and thematic clusters found in the selected literature concerning adoption and impact research in MI?
5. Who were the authors with the highest citation counts, and which journals were the most frequently cited in the references among the selected literature on the adoption and impact of MI research?

Following the responses to these inquiries, this study provided a discussion on the adoption and impact of MI.

2. METHODOLOGY

The study employed the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) technique (Figure 1) to conduct a systematic literature review, focusing on MI. The literature search was conducted using the Scopus database, employing various combinations of keywords such as knowledge, awareness, adoption, and impact related to MI domains. The search string incorporated diverse variations of keywords, Boolean operators, and truncation symbols to ensure the retrieval of relevant and robust results for subsequent analysis. Initially, all the selected articles were subjected to automatic analysis using VOSviewer, a software tool employed for constructing and visualizing bibliometric network diagrams used for this study.

VOSviewer was employed to methodically examine the content of the articles selected for the study. It is a software tool developed by the Research Centre for Science and Technology Studies at Leiden University in the Netherlands. It is a valuable tool utilized in this study to create and visualize bibliometric radial networks pertinent to precision irrigation investigation. These networks compiled information on journals, researchers, or individual publications and could be

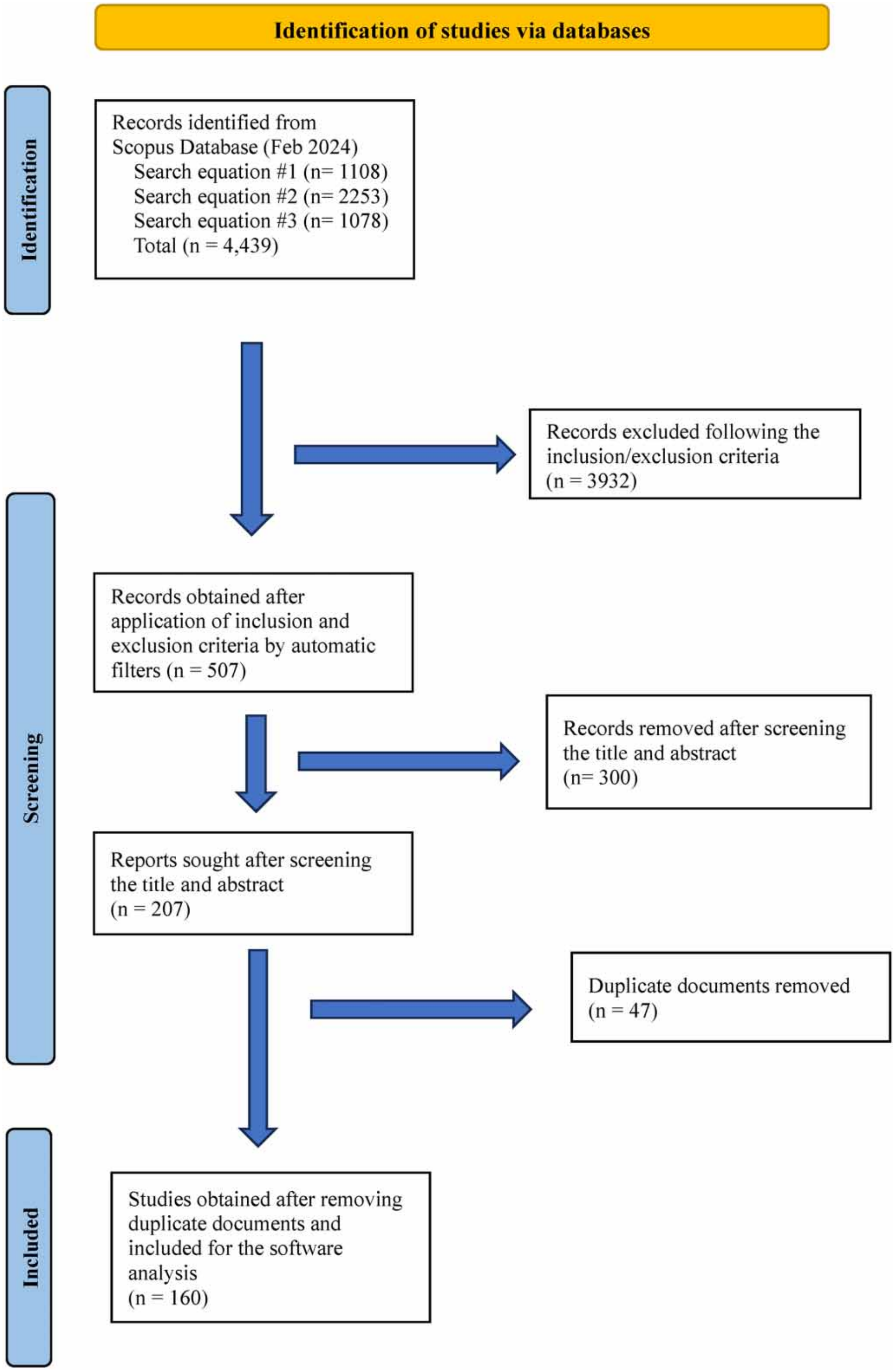


Figure 1 | PRISMA flow chart followed in the study for selecting documents.

constructed using relationships such as co-citation, bibliographic coupling, or co-authorship. Moreover, VOSviewer features a text mining capability that aids in constructing and illustrating co-occurrence networks, highlighting important terms extracted from the scientific literature. In VOSviewer's label view, various research elements are illustrated using coloured circles, with differences in the size of the circles and font sizes indicating the significance and hierarchical arrangement of each item (Liang *et al.* 2020). To obtain the articles analysed with the software, precise search equations were devised within the Scopus database. A distinct search equation was utilized to retrieve articles relevant to the exploration of adoption, knowledge, awareness, and impact concerning MI. This study employed three distinct search equations to comprehensively explore MI. The first equation (Table 1) focused on uptake, understanding, and consciousness by incorporating terms linked to awareness, knowledge and adoption of this technology. The second equation (Table 2) zoomed in on the consequences and influences of MI, utilizing terms associated with its impact and effect. Finally, the third equation (Table 3) examined the impact on finance, resource implications, water saving and yield, incorporating terms related to income, resource utilization, water conservation, and crop production. Each search term within every column was combined with each term in the other columns using the 'AND' operator. All search equations were applied to the article title, abstract, and keywords in the Scopus database.

After using the search equations, the following criteria (Table 4) were used for the inclusion and exclusion process:

Table 1 | The first search equation

Term 1	AND	Term 2	AND	Term 3	Results found	Results found after filtration
Adoption		Micro-irrigation			154	21
Knowledge		Micro-irrigation			130	27
Acceptance		Micro-irrigation			14	3
Adoption		Drip irrigation			367	77
Awareness		Drip irrigation			51	13
Knowledge		Drip irrigation			306	61
Perception		Drip irrigation			48	10
Adoption		Challenges		Drip irrigation	38	5
Total					1,108	217

Table 2 | The second search equation

Term 1	AND	Term 2	Results found	Results found after filtration
Impact		Micro-irrigation	577	70
Impact		Drip irrigation	1,352	36
Factor influencing		Micro-irrigation	37	5
Effect		Trickle irrigation	287	17
Total			2,253	128

Table 3 | The third search equation

Term 1	AND	Term 2	Results found	Results found after filtration
Weed control		Drip irrigation	106	22
Energy saving		Drip irrigation	37	4
Economic benefits		Drip irrigation	152	21
Sustainability		Drip irrigation	342	71
Water use efficiency		Trickle irrigation	75	7
Crop yield		Trickle irrigation	55	4
Efficiency		Trickle irrigation	163	14
Water use efficiency		Micro-irrigation	148	19
Total			1,078	162

Table 4 | Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Initial identification		
Time period	2013–2024	Before 2013
Subject area	Agricultural and Biological Sciences and Social Sciences	Environmental Science, Economics, Econometrics and Finance, Energy, Medicine, Business, Management and Accounting, Mathematics, Nursing, Multidisciplinary, Materials Science, Engineering, Immunology and Microbiology, Health Professions, Decision Sciences, Chemistry, Earth and Planetary Sciences, Chemical Engineering, Biochemistry, Genetics and Molecular Biology, Computer Science
Document type	Article	Book chapter, Conference paper, Review, Book
Language	English	Other than English
Source type	Journal	Book, Conference proceeding, Book series
Publication stage	Final	Press
Access type	Open access	Restricted access

3. RESULTS AND DISCUSSION

3.1. Publication trend in adoption and impact of MI research

Figure 2 (graph) portrays the progression of publications on MI from 2013 to 2024. It was evident that there was a consistent upward trend in the number of publications over the specified period, with a notable exception in 2021. During that year, publication rates dipped slightly, potentially due to the impact of the COVID-19 pandemic, which slowed down research activities. The publication rate in 2024 decreased due to the inclusion of data only for the month of January 2024. However, in 2022 and 2023, there was a significant surge in publications compared to the previous years, which indicated increasing global awareness and concern regarding water scarcity and the optimization of resources.

3.2. Most productive and influential authors and countries in the adoption and impact of MI research

Table 5 presents the primary contributors in the domain of MI, encompassing influential authors and nations. According to citation counts, Zaccaria D. from the University of California, USA, emerged as the most influential author in the domain of MI research, with 37 citations in his two publications, followed closely by Bloomberg M., Jia L., Li G., and Xi B., each with 32

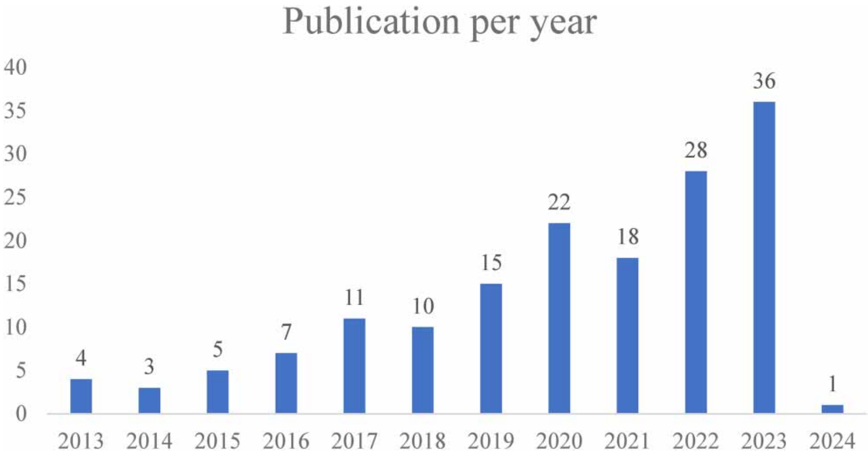


Figure 2 | Publication trend in adoption and impact of micro-irrigation research.

Table 5 | Primary authors and nations in the domain of micro-irrigation knowledge, adoption, and impact

TC	Author	TP	TC	Country	TP
37	Zaccaria D.	2	106	United States	6
32	Bloomberg M.	1	61	China	7
32	Jia L.	1	32	New Zealand	1
32	Li G.	1	23	Spain	3
32	Xi B.	1	19	India	4
22	Bai W.-B.	1	14	Ethiopia	1
22	Bali K.	1	14	South Africa	1
22	Carrillo-Cobo M.T.	1	13	Brazil	5
22	Gaudin A.C.M.	1	13	Italy	3
22	Kang Y.-H.	1	10	France	1
22	Liu Y.	1	10	Netherlands	1
22	Lü G.-H.	1	8	Egypt	1
22	Montazar A.	1	8	Lebanon	1
22	Peterson C.	1	8	Sri Lanka	1
22	Putnam D.H.	1	7	Australia	2

TC, total citations; TP, total publications.

citations and 1 publication. The United States leads influential countries with 106 citations from six publications, followed by China with 61 citations from 7 publications. New Zealand ranked third with 32 citations from 1 publication and demonstrated a high citations-per-publication (CPP) rate of 32 CPP, followed by the United States with 17.6 CPP, while Ethiopia and South Africa had 14 CPP each. Zaccaria D. stands out as the most productive author with two publications, while China emerged as the most productive country with seven publications centred on the adoption, knowledge, awareness, and impact assessment of MI techniques.

3.3. Co-authorship with authors

The co-authorship with author analysis (Figure 3) revealed insights into the collaborative networks among authors. In this analysis, Li Y. emerged as a prominent figure and collaborated with 25 other authors. The analysis organized authors into three distinct clusters based on their collaborative patterns and publication timeline.

The blue nodes represented authors whose works were primarily published between 2013 and 2016, indicating the era of collaboration. In contrast, the green nodes signify a unique cluster with Li Y. as the central figure, whose collaborative efforts peaked around 2019, distinguished from others. Finally, the yellow nodes, which denoted authors whose works were predominantly published between 2022 and 2023, showed a more recent collaborative trend in the network.

The co-authorship with author analysis unveiled nuanced collaborative dynamics among authors, delineated by time period and intensity of collaboration, with Li Y. playing a significant role across different clusters.

3.4. Co-occurrence – keywords

In co-occurrence analysis, terms were commonly sourced from ‘author keywords’ but can also be gleaned from ‘article titles,’ ‘abstracts’, and ‘full texts’. This analytical approach posits that frequently appearing keywords signify thematic connections. It served as a predictive tool for future research directions by incorporating relevant terms found within the paper’s context and anticipated analysis objectives. Through the examination of word associations, co-word analysis offers insights into emerging trends and potential areas of investigation within the field.

This co-occurrence analysis explored different thematic patterns concerned with awareness, knowledge, dissemination, adoption, and the impact of MI. All the keywords included for this analysis and a total of around 49 terms, each appearing at least twice in the literature. The size of each frame in Figure 4 showed the frequency of word occurrences in the literature corpus.

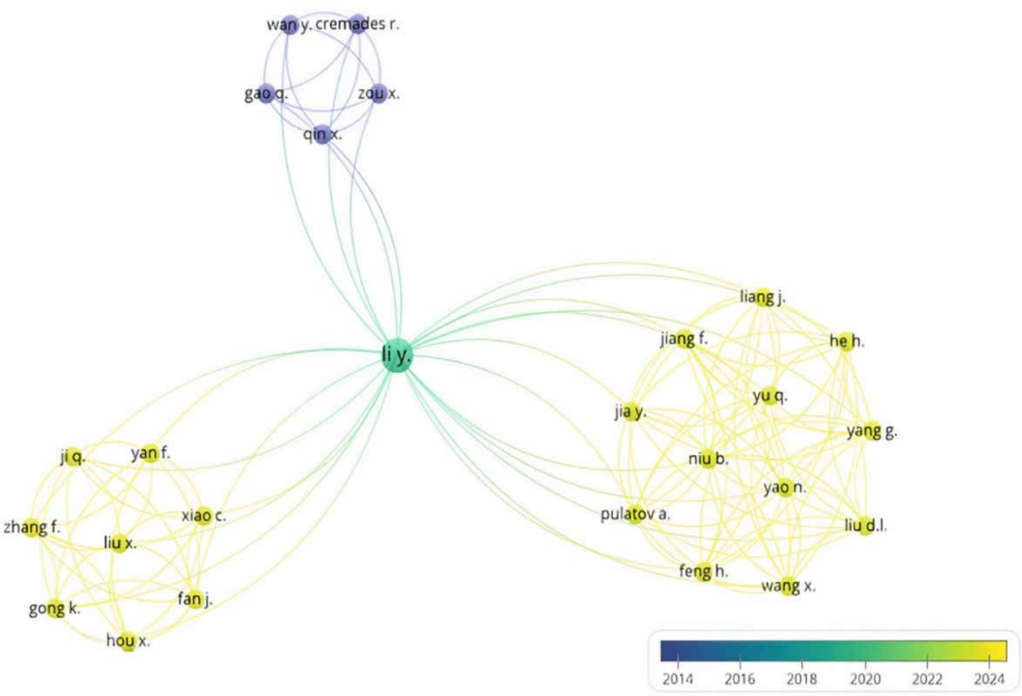


Figure 3 | Network of co-authorship with authors in the adoption and impact of micro-irrigation research.

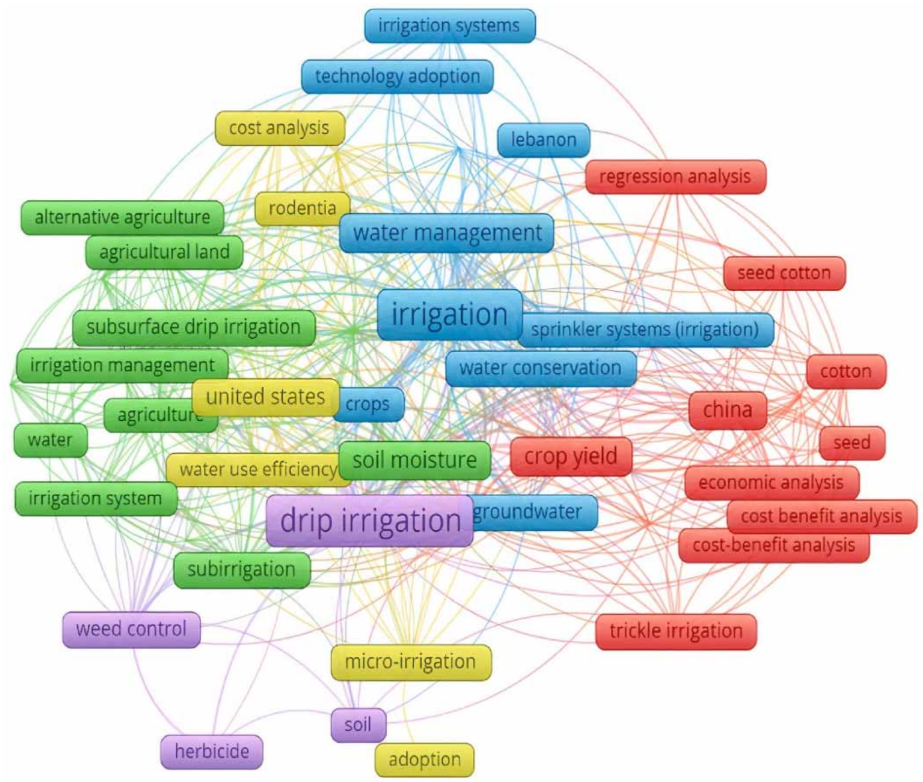


Figure 4 | Network of keywords trending in the adoption and impact of micro-irrigation research.

Notably, ‘Drip irrigation’ emerged as the most prominent term with 12 occurrences, closely followed by ‘Irrigation’ itself, which appeared 11 times. This prevalence suggests that a significant portion of past studies, particularly those revolving around drip irrigation, soil moisture dynamics, water management, and soil conditions, were conducted within the MI domain.

This analysis led to the classification of these keywords into five distinct clusters, each distinguished by a specific colour. Cluster 1, depicted in red frames, encompassed topics such as cost–benefit analysis, crop yield, and economic analysis, comprised of 13 terms.

Cluster 2, represented by green frames, explored the themes related to soil moisture, SDI, and irrigation management with 13 unique terms.

The serene blue frames of Cluster 3 highlighted the discussions surrounding irrigation, water management, and irrigation systems, encapsulating a total of 11 terms.

Cluster 4, characterized by yellow frames, delves into aspects such as water use efficiency, MI, adoption, and the United States with eight terms in total.

Lastly, Cluster 5, distinguished by violet frames, touched upon drip irrigation, weed control, herbicides, and soil featuring a concise compilation of four distinct terms.

Through this examination, the complex thematic links presented in discussions related to MI were identified and provided insights into potential paths for further scholarly investigation and research directions.

3.5. Co-authorship – organization

The analysis of co-authorship among organizations (Figure 5) revealed the extent of collaboration among institutions. Within the analysis, a total of 10 organizations were identified, including Al-Kut University College in Kut (Iraq), Ajman University (UAE), Gift University (Pakistan), Kurgan State University (Russia), N.P. Ogarev Mordovia State University (Russia), Saveetha University (India), The Islamic University (Iraq), Udayana University (Indonesia), Universitas Muhammadiyah Kalimantan Timur (Indonesia), and the University of Anbar (Iraq). Each of these institutions collaborates with one another, fostering a network of interconnected partnerships.

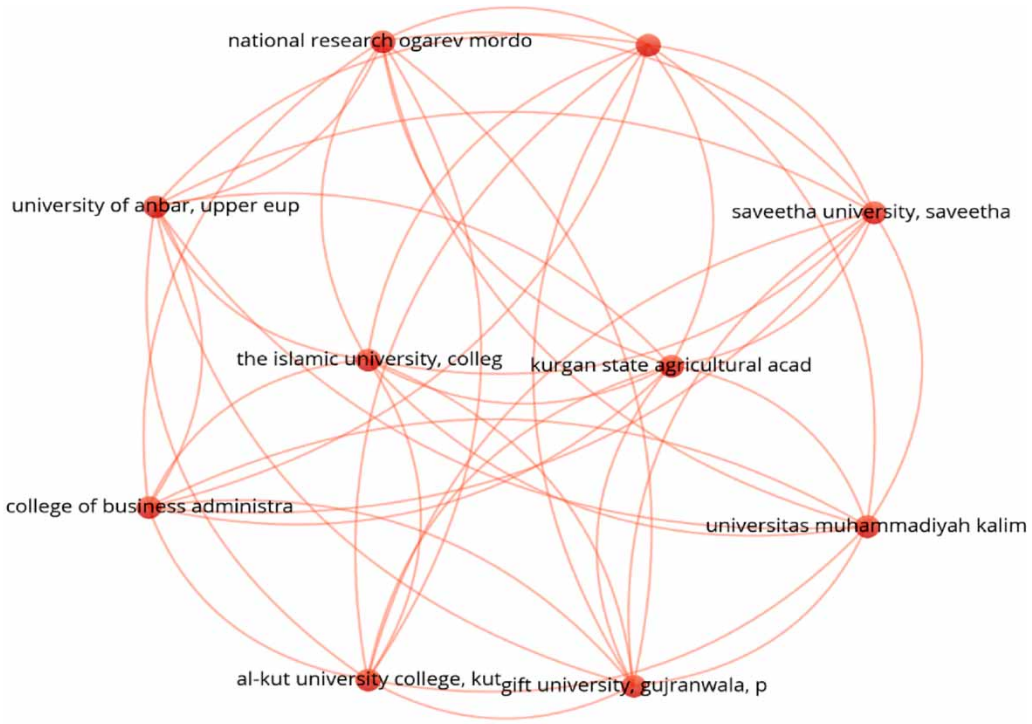


Figure 5 | Network of co-authorship with organization in the adoption and impact of micro-irrigation research.

Through these collaborations, institutions can share their innovative ideas and resources, contributing to the global effort to address various challenges. Such partnerships facilitated the exchange of knowledge and expertise, ultimately benefiting all participating organizations. By leveraging collective efforts, institutions could tackle the issues on a broader scale and derive mutual advantages from their collaborative endeavours.

3.6. Co-citation – cited authors

The co-citation analysis revealed the prominent authors referenced in the literature corpus. Figure 6 illustrates the network of co-cited authors who were cited at least three times in the collected literature. The size of the nodes corresponds to the number of citations in the referenced articles. Coelho E.F. emerged as the most frequently cited author with 15 citations, followed by Narayanmoorthy A. with 14 citations. Lamm F.R. was also among the most cited authors in the collected literature, with 11 citations, while Li Y. garnered nine citations. The co-citation analysis identified approximately six clusters among the cited authors.

3.7. Co-citation – cited sources

The top-cited journals in the realm of MI were identified through the semantic connections revealed by co-citation analysis, as shown in Figure 7. *Agricultural Water Management* emerged as the most referenced journal within the literature corpus, garnering 21 citations, followed by *Weed Technology* with 16 citations, *Science of the Total Environment* with nine citations, *Management Information System Quarterly* with 8 citations, and *Sustainability* with 7 citations, while *Plant and Soil* and *Field Crop Research* both accrue six citations. The journals were categorized into nine clusters based on the node's colour. *Management Information System Quarterly*, *World Development*, *Climate Change*, and *Information Systems Research* (red nodes) were highly cited journals within the literature corpus. *Science of the Total Environment*, *Sustainability*, and *Climate Risk Management* (green nodes) were also prominent in the areas of awareness, knowledge, adoption, and impact of MI. *Crop Science*, *Irrigation and Drainage*, and *World Development* (dark blue nodes) were highly cited journals in the field of MI. *Irrigation Science*, *International Journal of Water Resources Development*, and *International Journal of Innovation Management* (yellow nodes) were referred to in the domains of awareness, knowledge, adoption, and impact of MI. *Agriculture*, *Ecosystems & Environment*, *Field Crops Research*, and *Plant Soil* (violet nodes) were highly cited journals in the MI field. *Agricultural Water Management*, *Forest Research*, *Journal of Hydrology*, and *Forest Ecology and Management* (sky blue nodes) were prominent in the areas of awareness, knowledge, adoption, and impact of MI. *Science of the Total Environment*, *Food Chemistry*, *Chemosphere*, and *Water and Environment Journal* (orange nodes) were the most cited journals in MI research. *Weed Technology*, *Crop Protection*, and *HortScience* (brown nodes) were highly cited journals in the MI realm. *Agronomy Journal*, *Geoderma*, and *Plant and Soil* (purple nodes) were the journals cited in the domains of awareness, knowledge, adoption, and impact of MI. From this co-citation analysis, it was evident that *Agricultural Water Management*, *Weed Technology*, *Science of the Total Environment*, *Management Information System Quarterly*, and *Sustainability* were the

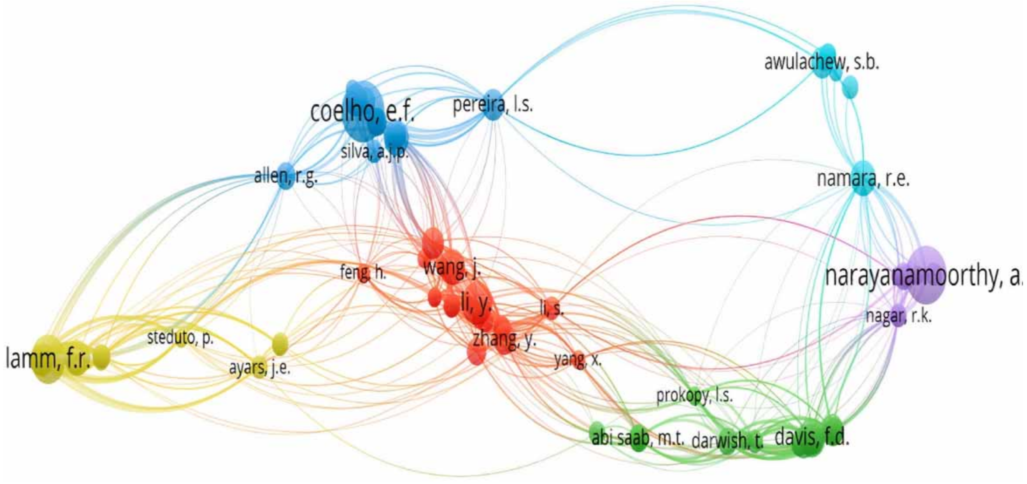


Figure 6 | Co-citation of authors cited in articles on the adoption and impact of micro-irrigation research.

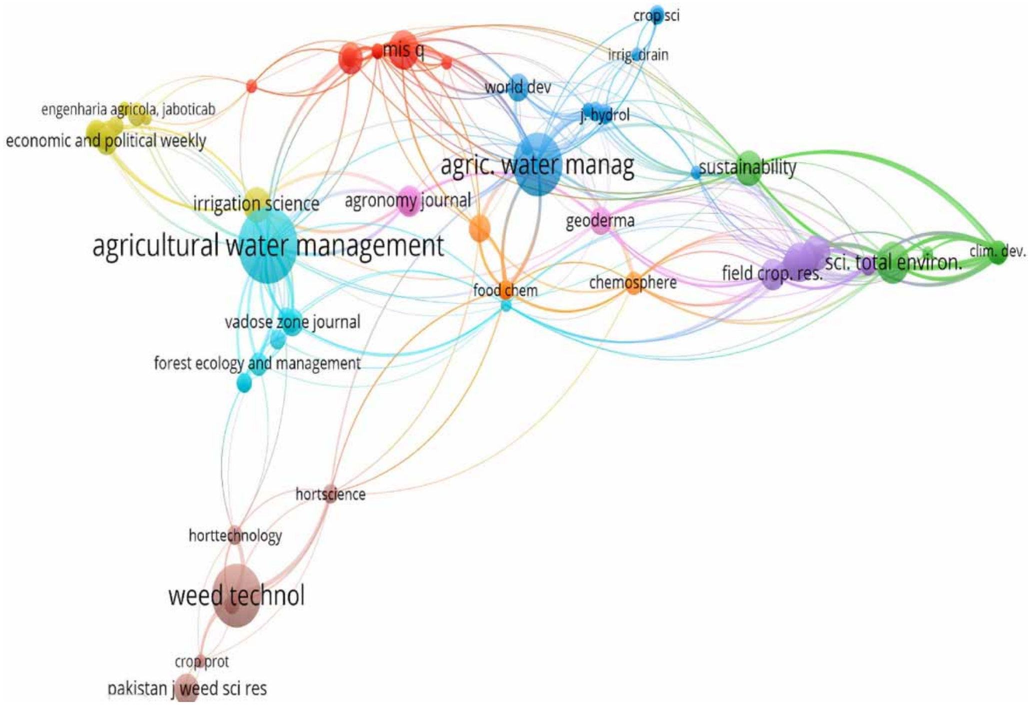


Figure 7 | Co-citation of sources cited by articles on the adoption and impact of micro-irrigation research.

primary journals that published and received significant citations within the domains of awareness, knowledge, adoption, and impact of MI.

3.8. Bibliography coupling – documents

Expanding upon the groundwork laid in the preceding section with the sourced materials and the gathered literature using bibliographic coupling techniques, bibliographic coupling was used to explore the connections among citing publications, grasp the evolving themes within a research field over time, and analyse the relationships among the cited works (Donthu *et al.* 2021). In contrast to co-citation analysis, which examined cited publications and emphasized influential works with high citation rates within the domain, bibliographic coupling relies on citing publications to elucidate existing knowledge within the field (Goodell *et al.* 2021). Consequently, this analysis would offer a depiction of the current state of the research field (Donthu *et al.* 2021). The bibliographic coupling analysis (Figure 8) revealed three thematic clusters, namely, the impact of irrigation water, weed control and crop production, and irrigation and organic cultivation. Table 6 also presents key influential articles from each cluster.

Cluster 1 focused on the effects on irrigation water. Xi *et al.* (2014) explored the impact of subsurface irrigation on the growth and transpiration of *Populus tomentosa* in the North China Plain and observed that SDI influenced soil water content

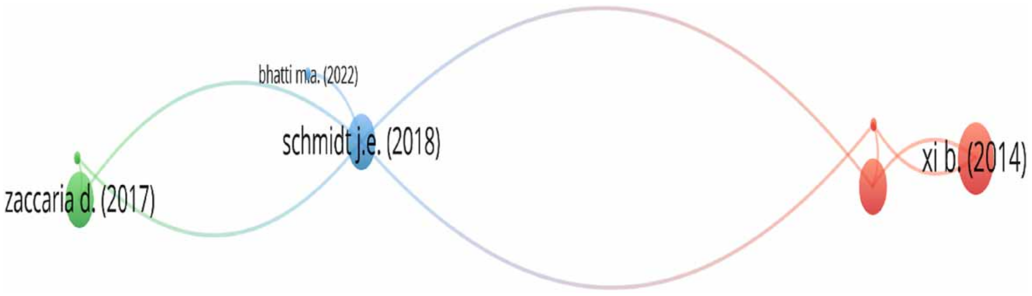


Figure 8 | Network of bibliographic coupling of documents in adoption and impact of micro-irrigation research.

Table 6 | Network of thematic clusters on the adoption and impact of micro-irrigation research

Theme	Authors	Title	Total citations
Effects of irrigation water	Xi *et al.* (2014)	The effects of subsurface irrigation at different soil water potential thresholds on the growth and transpiration of *Populus tomentosa* in the North China Plain	32
	LÜ *et al.* (2015)	Effects of different irrigation methods on micro environments and root distribution in winter wheat fields	22
	Dos Santos *et al.* (2020)	Yield and water use efficiency in 'Tommy Atkins' and 'Palmer' mango trees under localized irrigation with water deficit	3
Weed control and crop yield	Zaccaria *et al.* (2017)	Assessing the viability of subsurface drip irrigation for resource-efficient alfalfa production in central and Southern California	22
	Hakoomat *et al.* (2017)	Application of pre- and post-emergence herbicides under improved field irrigation systems proved a sustainable weed management strategy in cotton crop	3
Irrigation and organic cultivation	Schmidt *et al.* (2018)	Agroecosystem trade off associated with conversion to subsurface drip irrigation in organic systems	22
	Bhatti *et al.* (2022)	Micro Investment by Tanzanian Smallholders in Drip Irrigation Kits for Vegetable Production to Improve Livelihoods: Lessons Learned and a Way Forward	1

(SWC) within 0–80 cm soil depth but increased below 80 cm depth during heavy rain. SDI enhanced the above-ground dry mass (ADB) increment in *P. tomentosa* plantations. Lü *et al.* (2015) investigated the effects of various irrigation methods on microenvironments and root distribution in winter wheat fields and found that SDI maintained the highest soil matric potential during the irrigation period, affecting root distribution patterns. In the SDI treatment, the soil's elevated moisture content at a depth of 40–100 cm resulted in thicker roots compared to those observed in the sprinkler irrigation and border irrigation treatments. Dos Santos *et al.* (2020) studied the yield and water use efficiency of 'Tommy Atkins' and 'Palmer' mango trees under localized irrigation with a water deficit. Their findings suggested that 'Tommy Atkins' mango yield was higher with micro-sprinkler irrigation, while 'Palmer' mango trees showed better yield and water use efficiency with drip irrigation compared to micro-sprinkler irrigation.

Cluster 2 focused on weed control and crop yield. Zaccaria *et al.* (2017) conducted research on SDI for resource-efficient alfalfa production and observed slight yield increases (~5%) and moderate reductions in water usage (approximately 6–8%) based on experimental trials. Hakoomat *et al.* (2017) explored the application of pre- and post-emergence herbicides under improved field irrigation as a sustainable weed management strategy in cotton crops. Their findings indicated a significant reduction (19–24%) in the total weed density across all treatments utilizing drip irrigation practices compared to those relying on FI methods, particularly evident 60 days after sowing.

Cluster 3 encompasses studies focused on irrigation and organic cultivation. Schmidt *et al.* (2018) explored the transition to SDI within organic cultivation. Their study revealed notable enhancements in irrigation water productivity (IWP) with SDI compared to FI across both years, despite applying 17% less irrigation water in 2015 and 36% less in 2016 with SDI. Additionally, SDI treatments effectively suppressed weeds, with fewer than 0.15 weeds per square metre in both years. Weed density was significantly higher in FI compared to drip irrigation treatments, with a 30-fold difference in 2015 and a 100-fold difference in 2016. However, there was no discernible difference in weed density between single-drip irrigation and double-drip irrigation treatments. In a separate study, Bhatti *et al.* (2022) revealed that the micro-investment by Tanzanian smallholders in drip irrigation kits for vegetable production enhanced their livelihoods. Their findings indicated that partial budgeting analysis demonstrated increased revenue generation for most vegetable varieties with MI adoption.

4. ADOPTION AND IMPACT OF MI

4.1. Awareness and adoption of MI

The success of the technologies depends upon the adoption of the technologies by the farmers. Some studies showed that the awareness rate of drip/sprinkler irrigation was high (Sanjeevi 2019). However, there was a lack of awareness regarding the economic advantages associated with high-efficiency irrigation systems (Razzaq *et al.* 2018). Spreading awareness among the farmers regarding the economic advantages provided by high-efficiency irrigation systems could be accomplished to increase the adoption rate of MI technology among farmers. Few researchers revealed that the adoption of MI leads to a reduction in groundwater extraction only when the power connection is metered (Bahinipati & Viswanathan 2019; Fan *et al.* 2022).

The primary factors driving farmers' intention to adopt MI were subjective norms (SN), and it was noted that attitude was more important than perceived behavioural control (PBC) for drip irrigation adoption, and it was revealed that attitude was pivotal in driving technological change (Wang *et al.* 2023). Furthermore, the studies revealed three models focusing on socio-economic factors, social capital, and technology characteristics. Age, farmers' education regarding operation and upkeep, water resources and proximity to agricultural offices, level of education, diversity of products, and distance to urban centres come under socio-economic factors. Family, community, workplace, and availability of water storage facilities fell under social capital. Innovation, effective integration with fertilizer application, and drip design tailored to soil characteristics fell under the technology characteristics model. From these factors, access to credit, labour availability, education level, and costs associated with water extraction emerged as significant and positive factors influencing farmers' decisions on the adoption of MI. However, investment and farmers' age, information sources, membership in organizations, and subsidies exert a significant and negative impact on the adoption of MI (Belaidi *et al.* 2022; Sajid *et al.* 2022; Yazdanpanah *et al.* 2022).

Despite the numerous advantages of MI, the acceptance of MI (drip/sprinkler) was low among farmers (Sanjeevi 2019) due to the high installation cost, maintenance cost, and salt deposition. A few studies revealed that training enhanced the adoption of drip irrigation by farmers through active learning, social interaction, and the absorptive capacity of the drip fertigation system. Farmers who had received adequate training in the installation of drip irrigation had a tendency to adopt MI (Yang *et al.* 2021; Hussain *et al.* 2022). As mentioned earlier, the adoption of water-saving practices like drip irrigation has various challenges, such as infrastructure, installation cost, maintenance cost, system maintenance, water quality, drip blockage issues, lack of knowledge, organizational mode, rationale, social interaction, time, and space (Greenland *et al.* 2019; Wainaina 2021). Some studies showed that the government provided subsidies for the installation of MI systems, which improved the adoption rate. However, interestingly, one study stated that subsidies might not sufficiently incentivize small-scale farmers to embrace high-efficiency irrigation systems (Razzaq *et al.* 2018). The implementation of drip irrigation promoted the transition towards horticultural crops and also improved farmers' income (Fishman *et al.* 2023).

4.2. Impact of MI

As indicated earlier, the adoption of MI not only led to a reduction in the usage of water in agricultural fields but also had an impact on economic benefits, yield, energy, labour, productivity, weed control, and the environment. The study further discussed the economic benefits, water use efficiency, environment, energy, weed control, and yield in the subsequent paragraphs.

4.2.1. Impact of MI on economic benefits

Various studies showed considerable economic benefits to farmers' investment in MI technologies (Fan *et al.* 2022; Singh *et al.* 2023), and these returns on investment led to an increase in the adoption of MI. Several authors measured the economic benefits through the benefit–cost ratio (BCR) and net present value (NPV) as assessment tools and also to determine the viability of the technology (Kiruthika & Kumar 2020; Narayanamoorthy *et al.* 2020; Hussain *et al.* 2022).

Some studies revealed that profit could increase by 2.1% due to the adoption of drip irrigation with mulching (Nouri *et al.* 2020). However, a few studies mentioned that groundnut, apple and soyabean intercropping systems yielded economically superior benefits under different forms of MI, such as drip irrigation, drip irrigation with mulching, SDI, and bubbler irrigation. The farmers could recover the entire capital cost incurred for implementing drip systems in groundnut cultivation within the first year itself (Narayanamoorthy *et al.* 2020; Dai *et al.* 2023). Furthermore, in cotton planting, the biochar application rate under drip irrigation with mulching had higher economic benefits and an increase in quality and yield (Li *et al.* 2023b), whereas gross margins were increased for wheat and mango farms under high-efficiency irrigation systems (Razzaq *et al.* 2018).

A study economically compared low-head drip irrigation with high-head drip systems for different crops like dates, lemon, grapes, squash gourd, bitter gourd, and okra in different conditions. The study concluded that dates, lemon, grapes, and mixed fruit orchards had a high BCR in low-head drip irrigation systems, whereas crops like grapes, bitter gourd, and okra in rainfed conditions and squash gourd in irrigated conditions exhibited a high BCR in high head drip irrigation systems (Hussain *et al.* 2022). The evolution of the MI system also increased the economic condition of farmers growing different crops, as evident from the above-mentioned authors.

4.2.2. Impact of MI on water use efficiency

The adoption of MI had a great impact on water use efficiency. However, different types of MI on different crops had different levels of impact on water conservation. Some of the studies stated that the adoption of MI had high water use efficiency when compared with FI, surface irrigation, or flood irrigation (Table 7) (Narayanamoorthy *et al.* 2020; Singh *et al.* 2022; Li *et al.* 2023a).

However, in crops like wheat and maize, water use efficiency increased by up to 3 and 25.3% when compared with surface irrigation (Li *et al.* 2023a), whereas, in date palm, the increase in water use efficiency might be due to the direct application of water near the root zone of the crops.

Furthermore, Aziz *et al.* (2021) pointed out that conventional irrigation leads to roughly 50% of water loss through leaching into groundwater, and hence additional water requirements were created to meet the water loss. Several studies compared the water use efficiency between surface drip irrigation and SDI. From these studies, it was revealed that SDI had a greater impact on water use efficiency than surface drip irrigation (Ayars *et al.* 2017; Dehghanisanij *et al.* 2020; Palacios-Diaz *et al.* 2023). Further, in date palm the water use efficiency was significantly higher than in drip irrigation (Mohammed *et al.* 2021).

Interestingly, a few studies compared root zone MI with surface drip irrigation. In grapes, direct root zone irrigation effectively enhanced water use efficiency by 9–11% (Ma *et al.* 2020). However, in pepper, average water use efficiency was approximately 20.2% higher with root zone MI than with surface drip irrigation in red loam soil areas only, whereas in yellow sand soil, surface drip irrigation performed better than root zone MI by 16.6% (Zhang *et al.* 2020). It was clear that soil types also affect water use efficiency. A few studies revealed that the moisture level in the micro-sprinkler plastic film, drip irrigation plastic film, and mulching system remained consistently 25–30% higher compared to conventional drip irrigation methods (Kadbhane & Manekar 2016; Li *et al.* 2022). However, a study revealed that drip irrigation in conjunction with mulching outperformed conventional surface irrigation, surface irrigation with mulching, and sole drip irrigation (Samui *et al.* 2020).

4.2.3. Impact of MI on weed growth

Most of the studies revealed that the implementation of drip irrigation leads to a reduction in weed growth compared to conventional irrigation methods like FI and surface irrigation. However, a few studies revealed that under sugar beet cultivation, the infestation of weed growth was reduced by 8–10 times when compared to surface irrigation (Kenenbayev *et al.* 2016), whereas in cotton crops, the reduction in weed growth was noticed in drip-irrigated fields compared to the furrow method of irrigation (Hakoomat *et al.* 2017). Further, drip irrigation reduced the costs associated with weeding in groundnut crops (Narayanamoorthy *et al.* 2020). The reduction in costs for weeding might be due to the lower growth of weeds under drip irrigation.

Some studies revealed that weed biomass was notably reduced under SDI compared with drip irrigation (Ayars *et al.* 2017). Further, weed occurrence was reduced under SDI compared to drip irrigation in maize (Dehghanisanij *et al.* 2020). The reduction in weed growth in the case of drip irrigation might be due to the targeted application of water to the root zone

Table 7 | Crop-wise water saving percentage compared to conventional irrigation

Crop	Water savings compared to conventional irrigation (%)
Onion	18
Cabbage	18
Pepper	14
Garlic	28

Source: Yimam *et al.* (2020).

of plants, whereas in the case of SDI, water and nutrients were supplied directly to the crop root area, leading to less availability of water for weed growth.

4.2.4. Impact of MI on the environment and energy

As mentioned earlier, MI played a crucial role in water use efficiency, weed growth, yield, and economic benefits, and it also had an impact on the environment and energy. Some research studies revealed that when untreated wastewater was used for irrigation through drip and flood irrigation, the heavy metal deposition was comparatively low in drip irrigation (1.25–20%), whereas in flood irrigation, it exceeded 25% (Pal *et al.* 2023). However, when treated wastewater was used through flood and drip irrigation, water usage and grain yields were enhanced under drip irrigation with treated wastewater (Ouoba *et al.* 2022), whereas drip irrigation, when integrated with fertilizer, and air, resulted in notable enhancements in various soil parameters like microbial biomass, enzyme activities, and soil aeration (Lei *et al.* 2022). A few studies mentioned that drip and sprinkler irrigation proved to be efficient approaches for mitigating greenhouse gas emissions and reducing global warming potential (Mehmood *et al.* 2023). However, drip irrigation leads to an increase in methane uptake and a decrease in accumulated CO_2 emissions compared with sprinkler and border irrigation (Mehmood *et al.* 2021). In the concept of energy conservation, Narayanamoorthy *et al.* (2020) pointed out that drip irrigation leads to a reduction in electricity consumption by about 121 kWh per acre compared to conventional irrigation.

4.2.5. Impact of MI on yield

Most of the studies on MI indicated that it improved the production and productivity of crops. About half of the studies stated that the yield was increased in drip irrigation when compared to conventional irrigation methods and other water management technologies like precision land levelling and bed planting (Rizwan *et al.* 2018; Aziz *et al.* 2021; Ouoba *et al.* 2022), whereas maize grain yield was higher under drip fertigation compared to flood fertigation (Guo *et al.* 2022). Crops like carrot, tomato, and potato yield increased by 56–120% under drip irrigation systems compared to conventional irrigation methods (Dawit *et al.* 2020). High-efficiency irrigation systems like sprinklers and drip irrigation enhanced the yield of wheat and mango (Razzaq *et al.* 2018).

Some studies found that SDI treatments resulted in higher average yield and productivity than drip irrigation treatments (Carvalho *et al.* 2014; Ayars *et al.* 2017). In terms of biomass yield, SDI outperformed drip irrigation (Dehghanisanij *et al.* 2020), whereas subsurface drip fertigation enhanced seed cotton yield by 26.6% compared to surface flood irrigation (Singh *et al.* 2022). A study by Ma *et al.* (2020) revealed that direct root zone irrigation enhanced grape yield by 9–12%. The yield enhancement might be due to the direct application of water in the root zone, which facilitates deeper root penetration and nutrient uptake.

Some studies stated that drip irrigation under mulch increased the yield up to 71.1% in intercropping of apple-soyabean (Dai *et al.* 2023), whereas drip irrigation with straw mulch enhanced the yield of tomato (Samui *et al.* 2020). Both micro-sprinklers under plastic film and drip irrigation under plastic film treatment increased the tomato fruit yield within greenhouse settings (Li *et al.* 2022). A few studies that compared drip irrigation with sprinkler and border irrigation revealed that the increase in grain yield was higher in drip irrigation with 0.9–5.4% (Mehmood *et al.* 2021). From the above studies, it could be concluded that MI increased the yield compared to conventional irrigation methods.

5. CONCLUSION

The systematic review, based on a modified version of the PRISMA 2020 approach, proved to be an effective method for searching appropriate literature and excluding irrelevant literature. The systematic literature review revealed a growing body of research on the adoption and impact of MI in recent years. Thus, this emerging research area offers opportunities for contributions from various perspectives.

In terms of prominent authors and nations, Zaccaria D. from the University of California, Davis, USA, stands out as the most influential author, while the United States leads among influential nations in MI publication. Concerning collaboration among authors and institutions, Li Y. stands out as a significant author who collaborated with 25 other authors. Additionally, we identified 10 institutions as the most collaborative, and these institutions had worked together. In terms of keywords, drip irrigation, irrigation, water management, soil moisture, SDI, and crop yield emerge as the most frequently occurring terms across the selected literature.

Among the most referenced authors in the selected literature, a network was constructed with the authors cited at least three times in the collected literature. Coelho was identified as the most cited author in the reference list of the literature corpus. In relation to the most referenced journals in the reference section of the selected literature, a network was established to highlight the most cited journals within the literature corpus. *Agricultural Water Management* emerged as the most frequently cited journal among the collected literature.

The adoption of MI technologies has significantly contributed to water conservation. According to various authors' findings, factors such as performance expectancy, effort expectancy, behavioural intention, and risk aversion influenced the adoption of MI. Furthermore, adopting MI leads to higher farm income and a shift towards horticultural crops. Attitude also played a pivotal role in technology adoption. Additionally, the adoption of water-saving irrigation technologies influenced access to credit and the costs associated with water extraction, affecting farmers' decisions. Despite farmers' high awareness of MI, technology adoption remains low in certain areas.

Regarding the impact of MI, it generated economic advantages through an increase in the BCR. Drip irrigation specifically resulted in various impacts, including higher chlorophyll content and leaf area index with reduced nitrogen application rates. SDI, in certain instances, enhances water productivity and boosts yields with reduced irrigation water requirements. Overall, MI significantly improved water use efficiency and yield.

These findings were valuable for both newcomers and experts in identifying the top authors and countries in the domain of adoption and the impact of MI. It also enabled the discovery of leading authors and journals in the MI fields, along with thematic clusters prevalent in current research. Additionally, this study provided insights into prominent authors and institutions, their collaborative networks, and trending topics in the field.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict of interest.

REFERENCES

Alcon, F., De Miguel, M. D. & Burton, M. 2011 Duration analysis of adoption of drip irrigation technology in southeastern Spain. *Technological Forecasting and Social Change* **78**, 991–1001.

Aqueduct, W. R. I. 2024 *Fresh Water*. Available from: https://www.wri.org/aqueduct (accessed 25 February 2024).

Ayars, J. E., Phene, C. J., Phene, R. C., Gao, S., Wang, D., Day, K. R. & Makus, D. J. 2017 Determining pomegranate water and nitrogen requirements with drip irrigation. *Agricultural Water Management* **187**, 11–23.

Azadi, Y., Yazdanpanah, M., Forouzani, M. & Mahmoudi, H. 2019 Farmers' adaptation choices to climate change: A case study of wheat growers in Western Iran. *Journal of Water and Climate Change* **10**, 102–116.

Aziz, M., Rizvi, S. A., Iqbal, M. A., Syed, S., Ashraf, M., Anwer, S., Usman, M., Tahir, N., Khan, A. & Asghar, S. 2021 A sustainable irrigation system for small landholdings of rainfed Punjab, Pakistan. *Sustainability* **13**, 11178.

Bahinipati, C. S. & Viswanathan, P. 2019 Can micro-irrigation technologies resolve India's groundwater crisis? Reflections from dark-regions in Gujarat. *International Journal of the Commons* **13** (2), 848–858.

Belaidi, S., Chehat, F. & Benmehaia, M. A. 2022 The adoption of water-saving irrigation technologies in the Mitidja plain, Algeria: An econometric analysis. *New Medit: Mediterranean Journal of Economics, Agriculture and Environment = Revue Méditerranéenne D'economie, Agriculture et Environment* **21**, 53–73.

Bhaskar, K., Rao, M., Mendhe, P. & Suryavanshi, M. 2005 *Micro Irrigation Management in Cotton*.

Bhatti, M. A., Godfrey, S. S., Divon, S. A., Aamodt, J. T., Øystese, S., Wynn, P. C., Eik, L. O. & Fjeld-Solberg, Ø. 2022 Micro-investment by Tanzanian smallholders' in drip irrigation kits for vegetable production to improve livelihoods: Lessons learned and a way forward. *Agriculture* **12**, 1732.

Bilgi, M. 1999 *Socio-economic Study of the IDE-Promoted Micro Irrigation Systems in Aurangabad and Bijapur*. International Development Enterprises, New Delhi.

Carvalho, G. C., Coelho, E. F., Da Silva, A. D. S. & Pamponet, A. J. 2014 Trickle irrigation: Effects on papaya crop. *Engenharia Agrícola* **34**, 236–243.

Dai, H., Wang, R., Chen, L., Wang, L., Xiong, C., Wang, X. & Zhang, M. 2023 Effects of different micro-irrigation methods on water use and the economic benefits of an apple–soybean intercropping system. *Agronomy* **13**, 1143.

Dawit, M., Dinka, M. O. & Leta, O. T. 2020 Implications of adopting drip irrigation system on crop yield and gender-sensitive issues: The case of Haramaya district, Ethiopia. *Journal of Open Innovation: Technology, Market, and Complexity* **6**, 96.

Dehghanisanij, H., Kanani, E. & Samira, A. 2020 Evapotranspiration and components of corn (*Zea mays* L.) under micro irrigation systems in a semi-arid environment. *Spanish journal of agricultural research* **18** (2), e1202.

Díaz, S., J, E, . Brondízio, S., Ngo, S., Guèze, H. T., Agard, M., Arneth, J., Balvanera, A., Brauman, P., Butchart, K. A., Chan, S. H. M., Garibaldi, K. M. A., Ichii, L. A., Liu, K., Subramanian, J., Midgley, S. M., Miloslavich, G. F., Molnár, P., Obura, Z., Pfaff, D., Polasky, A., Purvis, S., Razzaque, A., Reyers, J., Roy Chowdhury, B., Shin, R., Visseren-Hamakers, Y. J., Willis, I. J. & Zayas, K. J., C. N., eds. 2019 *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. IPBES secretariat, Bonn, Germany.

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N. & Lim, W. M. 2021 How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research* **133**, 285–296.

Dos Santos, M. R., Junior, P. R. F. C., Mesquita, N. L. S., Donato, S. L. R. & Coelho, E. F. 2020 Yield and water use efficiency in 'Tommy Atkins' and 'Palmer' mango trees under localized irrigation with water deficit Produtividade e eficiência de uso da água em mangueiras 'Tommy Atkins'e 'Palmer'sob irrigação localizada com déficit hídrico. *Semina: Ciências Agrárias, Londrina* **41**, 2509–2522.

Fan, Y., Himanshu, S. K., Ale, S., Delaune, P. B., Zhang, T., Park, S. C., Colaizzi, P. D., Evett, S. R. & Baumhardt, R. L. 2022 The synergy between water conservation and economic profitability of adopting alternative irrigation systems for cotton production in the Texas high plains. *Agricultural Water Management* **262**, 107386.

Field, C. B. & Barros, V. R. 2014 *Climate Change 2014 – Impacts, Adaptation and Vulnerability: Regional Aspects*. Cambridge University Press, Cambridge, UK.

Fishman, R., Gine, X. & Jacoby, H. G. 2023 Efficient irrigation and water conservation: Evidence from South India. *Journal of Development Economics* **162**, 103051.

Gerten, D., Heck, V., Jägermeyr, J., Bodirsky, B. L., Fetzer, I., Jalava, M., Kummu, M., Lucht, W., Rockström, J. & Schaphoff, S. 2020 Feeding ten billion people is possible within four terrestrial planetary boundaries. *Nature Sustainability* **3**, 200–208.

Goodell, J. W., Kumar, S., Lim, W. M. & Pattnaik, D. 2021 Artificial intelligence and machine learning in finance: Identifying foundations, themes, and research clusters from bibliometric analysis. *Journal of Behavioral and Experimental Finance* **32**, 100577.

Greenland, S., Levin, E., Dalrymple, J. F. & O'mahony, B. 2019 Sustainable innovation adoption barriers: Water sustainability, food production and drip irrigation in Australia. *Social Responsibility Journal* **15**, 727–741.

Grewal, S., Lohan, H. & Dagar, J. 2021 Micro-irrigation in drought and salinity prone areas of Haryana: Socio-economic impacts. *Journal of Soil Salinity and Water Quality* **13**, 94–108.

Guo, D., Chen, C., Zhou, B., Ma, D., Batchelor, W. D., Han, X., Ding, Z., Du, M., Zhao, M. & Li, M. 2022 Drip fertigation with relatively low water and N input achieved higher grain yield of maize by improving pre-and post-silking dry matter accumulation. *Sustainability* **14**, 7850.

Hakoomat, A., Arooj, M., Sarwar, N., Areeb, A., Shahzad, A. & Hussain, S. 2017 Application of pre and post emergence herbicide under improved field irrigation system proved a sustainable weed management strategy in cotton crop. *Planta Daninha* **35**, e017158976.

Hussain, A., Majeed, S., Hassan, A., Khathian, M. A., Khan, M. Z. U., Raza, I. & Bajkani, J. K. 2022 Adoption and cost-benefit analysis of drip irrigation for production of high-value crops in Pakistan: Drip irrigation for production of high value crops. *Proceedings of the Pakistan Academy of Sciences: B. Life and Environmental Sciences* **59**, 57–68.

Kadbhane, S. J. & Manekar, V. L. 2016 An experimental study of the surface and subsurface irrigation methods with respect to soil moisture on grape yard. *Journal of Water and Land Development* **31**, 73.

Kenenbayev, S. B., Ospanbayev, Z. O., Kydyrov, A. K., Musagodzhaev, N. T. & Aristangulov, S. S. 2016 Effectiveness of sugar beet cultivation under drop irrigation in South-East Kazakhstan. *Biosciences Biotechnology Research Asia* **13**, 917–924.

Khalid, S., Shahid, M., Natasha, B., Sarwar, I., Shah, T., & Niazi, A. H. & K, N. 2018 A review of environmental contamination and health risk assessment of wastewater use for crop irrigation with a focus on low and high-income countries. *International Journal of Environmental Research and Public Health* **15**, 895.

Kiruthika, S. & Kumar, D. S. 2020 Socio-economic impacts of the adoption of MIS (micro-irrigation system) among small and marginal farmers of Coimbatore district, India. *Journal of Applied and Natural Science* **12**, 312–318.

Lei, H., Yu, J., Zang, M., Pan, H., Liu, X., Zhang, Z. & Du, J. 2022 Effects of water-fertilizer-air-coupling drip irrigation on soil health status: Soil aeration, enzyme activities and microbial biomass. *Agronomy* **12**, 2674.

Li, Y., Zhang, M., Lu, Z., Zhang, Y. & Wang, J. 2022 Effects of irrigation strategy and plastic film mulching on soil N_2O emissions and fruit yields of greenhouse tomato. *Agriculture* **12**, 296.

Li, H., Li, X., Mei, X., Nangia, V., Guo, R., Hao, W. & Wang, J. 2023a An alternative water-fertilizer-saving management practice for wheat-maize cropping system in the North China Plain: Based on a 4-year field study. *Agricultural Water Management* **276**, 108053.

Li, Y., Yao, N., Liang, J., Wang, X., Niu, B., Jia, Y., Jiang, F., Yu, Q., Li Liu, D. & Feng, H. 2023b Rational biochar application rate for cotton nutrient content, growth, yields, productivity, and economic benefits under film-mulched trickle irrigation. *Agricultural Water Management* **276**, 108079.

Liang, Z., Liu, X., Xiong, J. & Xiao, J. 2020 Water allocation and integrative management of precision irrigation: A systematic review. *Water* **12**, 3135.

Liu, J., Hertel, T. W., Lammers, R. B., Prusevich, A., Baldos, U. L. C., Grogan, D. S. & Frolking, S. 2017 Achieving sustainable irrigation water withdrawals: Global impacts on food security and land use. *Environmental Research Letters* **12**, 104009.

Liu, X., Liu, W., Tang, Q., Liu, B., Wada, Y. & Yang, H. 2022 Global agricultural water scarcity assessment incorporating blue and green water availability under future climate change. *Earth's Future* **10**, e2021EF002567.

Lü, G.-H., Song, J.-Q., Bai, W.-B., Wu, Y.-F., Yuan, L. & Kang, Y.-H. 2015 Effects of different irrigation methods on micro-environments and root distribution in winter wheat fields. *Journal of Integrative Agriculture* **14**, 1658–1672.

Ma, X., Sanguinet, K. A. & Jacoby, P. W. 2020 Direct root-zone irrigation outperforms surface drip irrigation for grape yield and crop water use efficiency while restricting root growth. *Agricultural Water Management* **231**, 105993.

Mehmood, F., Wang, G., Gao, Y., Liang, Y., Zain, M., Rahman, S. U. & Duan, A. 2021 Impacts of irrigation managements on soil CO_2 emission and soil CH4 uptake of winter wheat field in the North China plain. *Water* **13**, 2052.

Mehmood, F., Wang, G., Abubakar, S. A., Zain, M., Rahman, S. U., Gao, Y. & Duan, A. 2023 Optimizing irrigation management sustained grain yield, crop water productivity, and mitigated greenhouse gas emissions from the winter wheat field in north China plain. *Agricultural Water Management* **290**, 108599.

Mohammed, M., Sallam, A., Munir, M. & Ali-Dinar, H. 2021 Effects of deficit irrigation scheduling on water use, gas exchange, yield, and fruit quality of date palm. *Agronomy* **11**, 2256.

Narayanamoorthy, A. 2003 Averting water crisis by drip method of irrigation: A study of two water-intensive crops. *Indian Journal of Agricultural Economics* **58**, 427–437.

Narayanamoorthy, A., Devika, N., Suresh, R. & Sujitha, K. 2020 Efficiency and viability of drip method of irrigation in groundnut cultivation: An empirical analysis from south India. *Water Policy* **22**, 1109–1125.

Nouri, H., Stokvis, B., Borujeni, S. C., Galindo, A., Brugnach, M., Blatchford, M., Alaghmand, S. & Hoekstra, A. 2020 Reduce blue water scarcity and increase nutritional and economic water productivity through changing the cropping pattern in a catchment. *Journal of Hydrology* **588**, 125086.

OECD, A 2011 Green growth strategy for food and agriculture. *Preliminary Report*.

Ouoba, N., Phung, L. D., Sasaki, A., Pham, D. V. & Watanabe, T. 2022 Drip fertigation with treated municipal wastewater and soil amendment with composted sewage sludge for sustainable protein-rich rice cultivation. *Environmental Technology & Innovation* **28**, 102569.

Pal, S., Patel, N., Malik, A., Sharma, A., Pal, U., Rosin, K. & Singh, D. 2023 Eco-friendly treatment of wastewater and its impact on soil and vegetables using flood and micro-irrigation. *Agricultural Water Management* **275**, 108025.

Palacios-Diaz, M. D. P., Fernández-Vera, J. R., Hernández-Moreno, J. M., Amorós, R. & Mendoza-Grimón, V. 2023 Effect of irrigation management and water quality on soil and sorghum bicolor Payenne yield in Cape Verde. *Agriculture* **13**, 192.

Pastor, A., Palazzo, A., Havlik, P., Biemans, H., Wada, Y., Obersteiner, M., Kabat, P. & Ludwig, F. 2019 The global nexus of food–trade–water sustaining environmental flows by 2050. *Nature Sustainability* **2**, 499–507.

Rahimi-Feyzabad, F., Yazdanpanah, M., Burton, R. J., Forouzani, M. & Mohammadzadeh, S. 2020 The use of a Bourdieusian 'capitals' model for understanding farmer's irrigation behavior in Iran. *Journal of Hydrology* **591**, 125442.

Razzaq, A., Rehman, A., Qureshi, A. H., Javed, I., Saqib, R. & Iqbal, M. N. 2018 An economic analysis of high efficiency irrigation systems in Punjab, Pakistan. *Sarhad Journal of Agriculture* **34**, 818–826.

Rizwan, M., Bakhsh, A., Li, X., Anjum, L., Jamal, K. & Hamid, S. 2018 Evaluation of the impact of water management technologies on water savings in the lower Chenab canal command area, Indus River basin. *Water* **10**, 681.

Sajid, I., Tischbein, B., Borgemeister, C. & Flörke, M. 2022 Assessing barriers in adaptation of water management innovations under rotational canal water distribution system. *Agriculture* **12**, 913.

Samui, I., Skalicky, M., Sarkar, S., Brahmachari, K., Sau, S., Ray, K., Hossain, A., Ghosh, A., Nanda, M. K. & Bell, R. W. 2020 Yield response, nutritional quality and water productivity of tomato (*Solanum lycopersicum* L.) are influenced by drip irrigation and straw mulch in the coastal saline ecosystem of Ganges delta, India. *Sustainability* **12**, 6779.

Sanjeevi, S. 2019 A study on technological mitigation strategies of farmers to overcome drought situations in Namakkal District. *Agricultural Extension Journal* **3** (1), 31–34.

Schmidt, J. E., Peterson, C., Wang, D., Scow, K. M. & Gaudin, A. C. 2018 Agroecosystem tradeoffs associated with conversion to subsurface drip irrigation in organic systems. *Agricultural Water Management* **202**, 1–8.

Shah, T. & Keller, J. 2002 Micro-irrigation and the poor: A marketing challenge in smallholder irrigation development. In: *Private Irrigation in Sub-Saharan Africa: Regional Seminar on Private Sector Participation and Irrigation Expansion in sub-Saharan Africa, 22–26 October 2001, Accra, Ghana* (Sally, H. & Abernethy, C. L., eds.). International Water Management Institute, Food and Agriculture Organization, pp. 165–184.

Singh, K., Singh, P., Singh, M., Mishra, S. K., Iqbal, R., Al-Ashkar, I., Habib-Ur-Rahman, M. & El Sabagh, A. 2022 Sub-surface drip fertigation improves seed cotton yield and monetary returns. *Frontiers in Plant Science* **13**, 1038163.

Singh, K., Singh, M., Mishra, S. K., Soufan, W., Habib-Ur-Rahman, M. & El Sabagh, A. 2023 Reduced tillage and subsurface fertigation improve productivity and economic benefits in the cotton-wheat cropping system. *Frontiers in Sustainable Food Systems* **7**, 1185805.

Srivastava, R. C., Mohanty, S., Singandhuppe, R. B., Mohanty, R. K., Behera, M. S., Ray, L. I. & Sahoo, D. 2010 Feasibility evaluation of pressurized irrigation in canal commands. *Water Resources Management* **24**, 3017–3032.

Tong, T. & Elimelech, M. 2016 The global rise of zero liquid discharge for wastewater management: Drivers, technologies, and future directions. *Environmental Science & Technology* **50**, 6846–6855.

Upadhyay, B. 2003 Drip irrigation: An appropriate technology for women. *Appropriate Technology* **30**, 31.

Villalobos, F. J. & Fereres, E. 2016 *Principles of Agronomy for Sustainable Agriculture*. Springer, New York.

Wainaina, G. K. 2021 Challenges in adoption of water-saving practices: Perspective from drip irrigation adoption in Kenya. *World Water Policy* **7**, 74–87.

Wang, J., Liu, L., Zhao, K. & Wen, Q. 2023 Farmers' adoption intentions of water-saving agriculture under the risks of frequent irrigation-induced landslides. *Climate Risk Management* **39**, 100484.

Ward, F. A. & Pulido-Velazquez, M. 2008 Water conservation in irrigation can increase water use. *Proceedings of the National Academy of Sciences* **105**, 18215–18220.

Xi, B., Li, G., Bloomberg, M. & Jia, L. 2014 The effects of subsurface irrigation at different soil water potential thresholds on the growth and transpiration of *Populus tomentosa* in the north China plain. *Australian Forestry* **77**, 159–167.

Yang, Q., Zhu, Y. & Wang, F. 2021 Exploring mediating factors between agricultural training and farmers' adoption of drip fertigation system: Evidence from banana farmers in China. *Water* **13**, 1364.

Yazdanpanah, M., Hayati, D., Hochrainer-Stigler, S. & Zamani, G. H. 2014 Understanding farmers' intention and behavior regarding water conservation in the middle-east and north Africa: A case study in Iran. *Journal of Environmental Management* **135**, 63–72.

Yazdanpanah, M., Feyzabad, F. R., Forouzani, M., Mohammadzadeh, S. & Burton, R. J. 2015 Predicting farmers' water conservation goals and behavior in Iran: A test of social cognitive theory. *Land Use Policy* **47**, 401–407.

Yazdanpanah, M., Klein, K., Zobeidi, T., Sieber, S. & Löhr, K. 2022 Why have economic incentives failed to convince farmers to adopt drip irrigation in southwestern Iran? *Sustainability* **14**, 2055.

Yimam, A. Y., Assefa, T. T., Adane, N. F., Tilahun, S. A., Jha, M. K. & Reyes, M. R. 2020 Experimental evaluation for the impacts of conservation agriculture with drip irrigation on crop coefficient and soil properties in the Sub-Humid Ethiopian Highlands. *Water* **12**, 947.

Zaccaria, D., Carrillo-Cobo, M. T., Montazar, A., Putnam, D. H. & Bali, K. 2017 Assessing the viability of sub-surface drip irrigation for resource-efficient alfalfa production in central and southern California. *Water* **9**, 837.

Zhang, M., Lu, Z., Bai, Q., Zhang, Y., Qiu, X., Qin, H., Yang, H. & Wang, Y. 2020 Effect of microsprinkler irrigation under plastic film on photosynthesis and fruit yield of greenhouse tomato. *Journal of Sensors* **2020**, 1–14.

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