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ARTICLE

A bibliometric analysis of scientific literature on alternate wetting and drying (AWD)

Rina Vuciterna[1] · Giordano Ruggeri[1] · Stefano Corsi[1] · Arianna Facchi[1] · Olfa Gharsallah[1]

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Abstract

The study presents a bibliometric analysis of scientific literature on alternate wetting and drying (AWD) as a water-saving irrigation practice for rice cultivation. Data were collected from the Web of Science, resulting in a database of 439 articles written by 2574 authors in 167 journals. The study reveals the growing importance of AWD in publications from the 90s to mid-2022, with fast growth and reaching its peak in the last 5 years, suggesting that the full potential of AWD remains yet to be realised and explored. Most papers are produced in oriental countries, except the USA and Australia. The trend of keywords in the research on AWD reveals a persistence of certain themes throughout the years while simultaneously showcasing a clear evolution of the topics being addressed. In addition to optimising productivity and agricultural yields, research now encompasses environmental issues and human and crop health, reflecting a broader trend in agriculture and research towards sustainable and environmentally responsible practices. This analysis provides insights into the development and direction of research in AWD, emphasising the need for future research to address the emerging concerns of the impact of AWD on the environment, human and crop health, and economic profitability of AWD adoption.

Keywords Bibliometric analysis · Alternate wetting and drying · AWD · Irrigation · Water management · Rice

Introduction

The supply of water to food crops presents an urgent global challenge, undermining the world's capacity to ensure food security and sustainable development prospects. Recent data reveal that irrigated agriculture, which constitutes 20% of all cultivated land, is responsible for approximately 40% of global food production and accounts for 70% of freshwater usage worldwide (World Bank 2022). In 2015, irrigation represented 42% of the total freshwater withdrawals in the USA (USDA 2022). Remarkably, even though less than 20% of the arable land was irrigated—encompassing 23.5 million out of 364.2 million hectares—this irrigated farmland contributed to more than 54% of the total value of U.S. crop sales (USDA 2022). Available data for 2016 indicates that in Europe, 8.9% or 15.5 million hectares of the utilised agricultural land were suitable for irrigation, but only 10.2 million hectares were irrigated (European Commission 2019a). In Asia, the proportion of agricultural irrigated land is notably high, encompassing 37% of the continent's farmland. This represents a substantial 70% of the world's total irrigated land, which is estimated at 277 million hectares, and 73% of the worldwide volume of water utilised for agricultural purposes (Tatalovic 2009). In contrast, Africa's agricultural practices heavily depend on rainfed methods, with only a minimal portion of its farmland, approximately 13 million hectares or 6% of the total cultivated area, being equipped for irrigation (You et al. 2010).

Nevertheless, the prevalence of irrigation varies considerably across countries and regions depending on the type of crops and varieties, climate, availability of water sources, type of agriculture, irrigation technology, irrigation

✉ Stefano Corsi
stefano.corsi@unimi.it

Rina Vuciterna
rina.vuciterna@unimi.it

Giordano Ruggeri
giordano.ruggeri@unimi.it

Arianna Facchi
arianna.facchi@unimi.it

Olfa Gharsallah
olfa.gharsallah@unimi.it

[1] Department of Agricultural and Environmental Sciences—Production, Landscape, Agroenergy, Università degli Studi di Milano, Via Celoria 2, 20133 Milan, Italy

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strategies, and socio-economic factors such as irrigation subsidies, water pricing and presence of other activities requiring water (Wriedt et al. 2009; Toan 2016; Hellegers et al. 2022).

The absence of irrigation would not just be a setback but a catastrophe for global agriculture. The production of key crops like rice, cotton, citrus, and sugar cane would plummet by 31–39%, and cereal production would take a staggering 47% hit, representing a 20% loss in total cereal production worldwide (European Commission 2019b).

Rice, wheat, and maise are the primary crops in irrigated farmlands globally, covering 102,386, 74,748, and 31,503 thousand hectares, respectively (FAO 2022) and provide about 50% of the global dietary energy, a figure that increases in developing countries (Poutanen et al. 2022). Specifically, rice is the most consumed cereal worldwide, sustaining over 3.5 billion people and accounting for more than 20% of global caloric intake, followed by wheat and maise, which have relatively higher use as feed (SRP 2020; Poole et al. 2021).

Traditional rice cultivation is particularly water-intensive, as it is grown in continuously flooded paddies from before sowing until harvest. This method requires significantly more water than non-ponded crops, positioning cereals, especially rice, as some of the largest consumers of water globally (Cesari de Maria et al. 2017; Facchi et al. 2018). While irrigated agriculture expanded substantially in the last century, recent trends and projections point to significant shifts in water availability for irrigation. In recent years, there has been a rise in water scarcity and competition globally due to escalating demands for industrial, domestic, and other uses, making a significant redistribution of water among competing sectors inevitable in the future. Moreover, climate change is anticipated to alter rainfall patterns, affecting both rainfed and irrigated agricultural systems (Rahman et al. 2017; Song et al. 2022). Between 1981 and 2005, water scarcity affected approximately 380 million hectares—39% of the world's croplands. Projections based on climate change scenarios predict this issue will intensify, with affected areas increasing by more than 3%, potentially bringing over 80% of global croplands under water scarcity (Liu et al. 2022). Plausible climate change scenarios include higher atmospheric carbon dioxide concentrations, temperatures, and precipitation changes (Timsina and Humphreys 2003; Trenberth 2008; Dehghan et al. 2019), and studies suggest that a one °C increase in global temperature could reduce rice yields by $3.2 \pm 3.7\%$, with maise and wheat experiencing even greater declines (Zhao et al. 2017).

In light of global population growth projections, the issues connected to irrigation take on even greater significance (Kashyap and Agarwal 2019). Indeed, given the demographic projections for the next decades, water scarcity is predicted to further exacerbate due to the combined effects of growing water withdrawals, the impacts of climate change, increasing demand and water quality degradation. Given these conditions, there is no way around watering crops using water more efficiently, in the right place, and in the right quantity. Even now, support for water in agriculture projects accounts for the largest share of the World Bank's support for agricultural productivity-related activities. The irrigated hectares in the United States have expanded from less than one million to over 24 million from 1890 to 2017 (USDA 2022), a growth made possible by water development projects and advancements in groundwater pumping technologies (USDA 2022). Meanwhile, globally, irrigation intensity has seen a decline in several regions, attributed to shifts in irrigated areas, changes in cropping patterns, and enhancements in the efficiency of water application technologies (USDA 2022).

While certain implemented or experimental solutions, such as water-efficient pressurised irrigation methods (Tarjuelo et al. 2015) and water desalination (Villaseñor and Ríos 2018), are highly technological and costly, some practices and management systems require very little technology and are available at low costs.

To address the challenges of feeding a growing global population under the pressures of climate change and water scarcity, several water-saving practices have been developed for irrigated rice cultivation (Zhou et al. 2017). Alternate wetting and drying (AWD) is a water-saving irrigation practice specifically developed for rice cultivation to reduce water usage (Linquist et al. 2015). The International Rice Research Institute (IRRI) pioneered the AWD technique in the 1990s and published formal guidelines for its implementation in 2002, standing apart from other intermittent flooding techniques that have been in use for decades (Lampayan et al. 2015). Under the AWD technique, rice fields are intermittently flooded and successively dried until the soil reaches a certain moisture level, then flooded again (Carrijo et al. 2017). Besides rice cultivation, the technique was also tested with other water-intensive crops, such as the medicinal plant Tulipa Edulis (Miao et al. 2015). Still, rice remains the main crop to adopt AWD irrigation.

In recent years, there has been a growing body of research on the impact of AWD on water use efficiency (WUE) and rice yield, comparing it to continuous flooding (CF) and other conventional farming practices (Norton et al. 2017). Findings are mixed: several studies suggest that AWD can increase grain yield over traditional management methods (Yang et al. 2009; Zhang et al. 2009; Ye et al. 2013; Chu et al. 2015), while others report no change in yield (Yao et al. 2012; Shaibu et al. 2015; Howell et al. 2015; Leon et al. 2021). Some research even indicates that AWD could reduce yield, particularly when the soil water content threshold before re-flooding is set too low (Humphreys et al. 2012; Zhou et al. 2017).

Given the critical need for water-saving strategies, AWD has been adopted and is highly recommended in several countries, including Bangladesh, Vietnam, the Philippines, and Myanmar (Lampayan et al. 2015). Furthermore, over the last 2 decades, AWD has gained recognition within the scientific community for its effectiveness in reducing irrigation requirements and yielding environmental benefits. This is evidenced by the presence of over 600 articles related to AWD in the Web of Science database from 1992 to the present, indicating significant academic interest and research activity.

A bibliometric analysis was conducted to gain insights into AWD research developments, trends, and future directions. This study explored various aspects of AWD-related research by retrieving and analysing publications from the Web of Science database spanning the last 30 years, from 1992 to mid-2022.

Methodology and search strategy

The approach adopted in this research is based on bibliometric analysis. Bibliometrics has been defined as a set of quantitative tools and methods to analyse different elements of scientific publications such as sources, research fields, authors, keywords, countries, citations, and co-authorships (Zupic and Čater 2014; Donthu et al. 2021). Bibliometric techniques can be classified into two distinct yet complementary categories: performance analysis and science mapping. Performance analysis is instrumental in assessing the contributions and impact of various research constituents, including the output and influence of authors, institutions, journals, and countries in the realm of academic research. It focuses on quantifying and evaluating the productivity and scholarly impact of these entities within the scientific community. On the other hand, science mapping provides tools to explore and visualise the complex relationships and networks among different elements of scientific publications. This encompasses an in-depth examination of the interrelations among authors, research fields, countries, and individual publications. Science mapping utilises techniques such as keyword co-occurrence networks and co-citation analysis to elucidate the dynamic and evolving nature of academic research, highlighting emerging trends, dominant themes, and foundational works in the field (Ruggeri et al. 2019; Donthu et al. 2021).

By integrating techniques from both performance analysis and science mapping, our methodology offers a comprehensive and nuanced understanding of the scholarly landscape, quantifying the contributions of various research entities and mapping the intricate web of connections that define and shape the field of study.

To conduct the bibliometric analysis of the AWD scientific literature, data has been retrieved from the Web of Science (WoS), an online scientific information support platform collecting more than 170 million publications (Donthu et al. 2021). Beyond providing access to publications, WoS provides the option to retrieve a wide set of information, such as titles, abstracts, keywords, and references, among others used in this study. The data extraction format was compatible with the statistical software used to analyse the data of this study, which was the reason for using WoS. The data was retrieved in May 2022, including the scientific literature from 1992 until mid-2022, using the following search parameters "alternate wetting and drying" or "alternate wetting drying". Brackets were used in the search query to ensure the presence of all the words included. Before the analysis, data was refined: the consistency of the publications collected concerning the AWD topic was verified by reading the titles and abstracts of all the documents; books and reviews were excluded, and only articles in the English language were retained. The final database consists of 439 papers written by 2574 authors in 167 journals.

The software BibExcel was used to clean and process the data, while CiteSpace and Vos viewer were used to analyse and create graphic representations. The first software was used primarily for performance analysis, while the other two were used to carry out science mapping, particularly co-citation.

Co-citation is one of the methodologies for science mapping based on the assumption that publications frequently cited together are thematically similar and heavily concur with research progress (Hjørland 2013). In a co-citation network, two articles are connected when they simultaneously appear in the reference list of one or more publications. The analysis can reveal the intellectual structure of a research field (Rossetto et al. 2018) and its underlying features (Liu et al. 2015). In Vos viewer, the clusterisation process within a co-citation network is executed through a technique called modularity-based clustering (Waltman and Van Eck 2013). This algorithm groups documents into clusters based on the density of their co-citation links, where a higher density of links within a group compared to between groups indicates thematic coherence. It essentially assesses the strength and frequency of co-citations, forming clusters that represent distinct thematic areas or research streams within the network.

While bibliometric analysis, particularly co-citation analysis, utilises the number of citations a paper has received as a basis for the analysis, it is important to note that the quantity of citations a paper has received does not correspond to the quality of the research. The primary purpose of the bibliometric analysis is not to assess the research's quality but to utilise the quantitative data associated with scientific publications to gain insights into the literature regarding a specific topic.

Results

Data overview

Table 1 and Fig. 1 illustrate the publication metrics in the AWD field, showcasing trends in scholarly output, citation impact, and collaborative authorship from 2004 to 2021. For a clearer year-on-year comparison, articles from 2022 were omitted. Although initial AWD research appeared in the early nineties, a consistent and growing body of studies emerged in 2004, marked by a steady publication volume and authorship growth. In 2004, the field had four publications by 21 authors; by 2021, these numbers had surged to 70 publications by 422 authors. The increased scientific interest became particularly pronounced after 2017, with the last five years witnessing the highest publication activity. Over the examined period, 2358 authors have contributed to 396 papers on AWD. While the average number of authors per paper increased modestly, citation numbers have significantly risen, hitting their peak in 2017 and 2018.

Table 1 The research trends on AWD

Year	Publications	Citations	Average citations	Standard deviation	Number of authors	Average authors per publication
2004	4	399	100	89.5	21	5.3
2005	4	212	53	33.2	11	2.8
2006	1	49	49	0	4	4.0
2007	6	320	53	46.6	27	4.5
2008	3	39	13	11.8	15	5.0
2009	7	485	69	57.0	37	5.3
2010	7	299	43	38.4	24	3.4
2011	14	691	49	41.6	63	4.5
2012	8	416	52	54.9	43	5.4
2013	8	525	66	70.3	46	5.8
2014	14	454	32	27.8	68	4.9
2015	26	804	31	39.3	128	4.9
2016	22	685	31	32.6	149	6.8
2017	37	922	25	43.0	245	6.6
2018	56	1101	20	16.0	377	6.7
2019	61	704	12	10.5	378	6.2
2020	48	314	7	5.9	300	6.3
2021	70	160	2	2.5	422	6.0

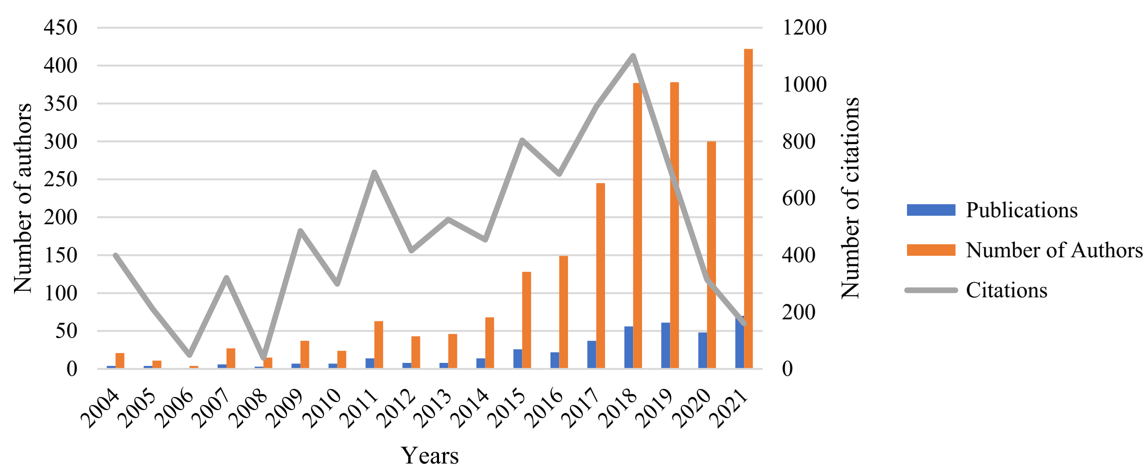


Fig. 1 Publication trends 2004–2021

Performance analysis

Most productive countries

Data for the 15 most active countries in AWD research are presented in Table 2, including the number of publications and citations, the percentage of the published articles, their cumulative percentage, and the average citations per document. Table 2 shows that research from the top four countries covers almost 50% of the total publications on the topic. Many of the most productive countries in AWD research, particularly in Asia, rely heavily on rice cultivation and consumption as key economic drivers and vital commodities for their populations. Moreover, AWD is primarily studied in countries that, despite historically sufficient access to irrigation water, are now facing drought crises due to climate change and are seeking more efficient irrigation solutions. China leads the list with the most articles published and citations, followed by India and the USA.

Furthermore, countries such as India, the Philippines, and Sri Lanka have also been particularly productive in researching the AWD topic. Although ranked third in published articles, the Philippines have a higher citation count than the USA. Research experiments in this field are typically conducted in the country of the corresponding author.

Table 3 presents the area cultivated with rice in hectares, rice production in tonnes and rice domestic supply in thousand tonnes, following the ranking of Table 2. The biggest producers and consumers are expected to be in the top two positions. However, it is noteworthy that India's production is lower than China's despite having a larger area cultivated with rice. The US, while having lower production, area cultivated, and consumption of rice compared to the top four positions in the table, remains highly competitive in publishing AWD articles, as Table 2 illustrates.

Most productive authors

The research community involved in studying AWD is growing, as Table 4 illustrates. This table identifies the most active authors in the database, detailing their number of AWD publications, years of research activity, and overall publication totals. These data points highlight their productivity and their commitment to AWD research.

Zhang, Jianhua, is the leading author on AWD, primarily involved in testing different rice cultivars developed in China, including 'super' rice cultivars aimed at improving agronomic and physiological traits (Zhou et al. 2017). His studies include comparing the yield of two super rice and two non-super rice cultivars under AWD and CF conditions (Zhou et al. 2017), assessing the reduction of cadmium content in rice through AWD (Yang et al. 2009), and investigating AWD's role in enhancing nitrogen availability in rice-microbe systems (Cao et al. 2022). Despite his notable contributions to AWD research, only 7% of Zhang's publications focus on this topic.

Islam, Mohammad Rafiqul (Islam MR), the second most prolific AWD researcher, has dedicated 64% of his work to this subject. His research emphasises AWD's environmental benefits, such as improving water management and reducing greenhouse gas emissions in rice paddies (Hossain and Islam 2022), and lowering methane and carbon emissions (Haque et al. 2021).

Table 2 Most productive countries—based on the corresponding author

Country—corresponding author	Articles published	Percentage (%)	Cumulative percentage (%)	No. of citations	Average citations
Peoples R China	139	18	18	3610	26
USA	74	10	28	1845	25
Philippines	71	9	37	2910	41
India	60	8	45	1138	19
Australia	44	6	51	1028	23
Bangladesh	43	6	57	571	13
Japan	34	4	61	555	16
Pakistan	28	4	65	454	16
UK	25	3	68	335	13
Thailand	22	3	71	313	14
Vietnam	21	3	74	341	16
Germany	20	3	76	304	15
Italy	16	2	78	180	11
France	13	2	80	121	9
Netherlands	13	2	82	287	22

Table 3 Area of rice cultivation, production and consumption per country in 2020

Country	Area harvested with rice (ha, thousands)[a]	Rice production (tonnes, thousands)[a]	Rice domestic supply (tonnes, thousands)[a]
Peoples R China	30,342	213,611	214,905
USA	1208	10,320	6255
Philippines	4719	19,295	22,220
India	45,769	186,500	160,166
Australia	5	50	488
Bangladesh	11,418	54,906	56,721
Japan	1462	10,469	10,249
Pakistan	3336	12,630	5061
UK[b]	0	0	1674
Thailand	10,944	31,734	19,500
Vietnam	7222	42,765	33,599
Germany[b]	0	0	619
Italy[b]	227	1507	689
France[b]	14	75	868
Netherlands[b]	0	0	587

[a]Food and Agriculture Organization of the United Nations-Agricultural Outlook 2017–2026

[b]FAOSTAT–Food balances

Table 4 Most productive authors in AWD research, publications and active years

Author	No. of publications	Active years		Total publications	Publications on AWD/total (%)
Zhang JH	22	2009	2021	305	7
Islam MR	16	2016	2022	25	64
Yang JC	13	2009	2021	126	10
Zhang H	12	2009	2021	68	18
Chen TT	12	2010	2022	254	5
Wang ZQ	12	2009	2021	191	6
Datta A	11	2018	2021	123	9
Ullah H	11	2018	2021	37	30
Sander BO	11	2015	2022	65	17
Humphreys E	10	2009	2017	70	14

Journal analysis

From 1992 to 2021, a total of 167 journals published scientific papers on AWD. Of these, the top five journals contributed 138 papers, accounting for over 25% of all articles published on this topic, as detailed in Table 5. Agricultural Water Management published the most papers leading the list, followed by Field Crops Research with 36 publications. The Paddy and Water Environment journal ranks third with 25 publications and holds the distinction of having the highest proportion of AWD articles relative to its total published articles.

Science categories

The top 20 science categories in AWD research are detailed in Table 6, highlighting Agriculture as the most dominant field with 285 articles, making up 41% of all publications. Environmental Sciences and Ecology follow this with 104 articles (15%), Water Resources with 77 articles (11%), and Plant Sciences with 70 articles (10%). Engineering contributes 25 articles, accounting for 4% of total output, while Science and Technology and other areas comprise 3% with 21 publications. Notably, the top four categories experienced a sharp increase in publications starting in 2018, with continued growth in the following years. In contrast, other categories have shown a steady increase. AWD publications have historically featured in categories like Agriculture, Environment, and Water. Over time, however, AWD research has diversified into more multidisciplinary fields, incorporating categories such as Mineralogy, Nutrition and Health.

Science mapping

Keyword co-occurrence networks

In this study, we utilise co-occurrence keyword analysis, as detailed by Sabour et al. (2022), to clarify the thematic structure and track the developmental trajectory of AWD research. This technique involves identifying and analysing the frequency and patterns of keywords appearing together in relevant literature. By mapping these co-occurrences, we can detect core themes, discern emerging trends, and understand the evolution of the field over time. In the visual

Table 5 Top 15 journals publishing on AWD

Source	AWD publications	Per cent (%)	Total citations	Total publications	Ratio AWD publications%
Agricultural Water Management	48	10.8	2273	6782	0.7
Field Crops Research	36	8.1	2145	5836	0.6
Paddy and Water Environment	25	5.6	678	963	2.6
Science of the Total Environment	17	3.8	274	53,544	0.0
Agronomy-Basel	12	2.7	44	7416	0.2
Soil Science and Plant Nutrition	10	2.3	264	3854	0.3
Agriculture Ecosystems & Environment	9	2.0	291	7852	0.1
Agronomy Journal	7	1.6	164	14,472	0.0
Water	7	1.6	43	16,184	0.0
Journal of Cleaner Production	7	1.6	70	29,599	0.0
Plant and Soil	6	1.4	63	16,816	1.8
Food and Energy Security	6	1.4	133	338	0.3
Irrigation and Drainage	6	1.4	15	1745	0.0
Communications in Soil Science and Plant Analysis	5	1.1	27	8876	0.3
Archives of Agronomy and Soil Science	5	1.1	83	1699	0.1

Table 6 Top 20 science categories of WoS on AWD

Science categories	Total	Science categories	Total
Agriculture	285	Life Sciences and Biomedicine-Other	4
Environmental Sciences and Ecology	104	Biotechnology and Applied Microbiology	3
Water Resources	77	Toxicology	3
Plant Sciences	70	Forestry	3
Engineering	25	Genetics and Heredity	3
Science and Technology–Other Topics	21	Geochemistry and Geophysics	3
Food Science and Technology	18	Mineralogy	2
Chemistry	15	Nutrition and Diabetics	2
Geology	13	Biochemistry and Molecular Biology	2
Meteorology and Atmospheric Sciences	10	Biodiversity and Conservation	2

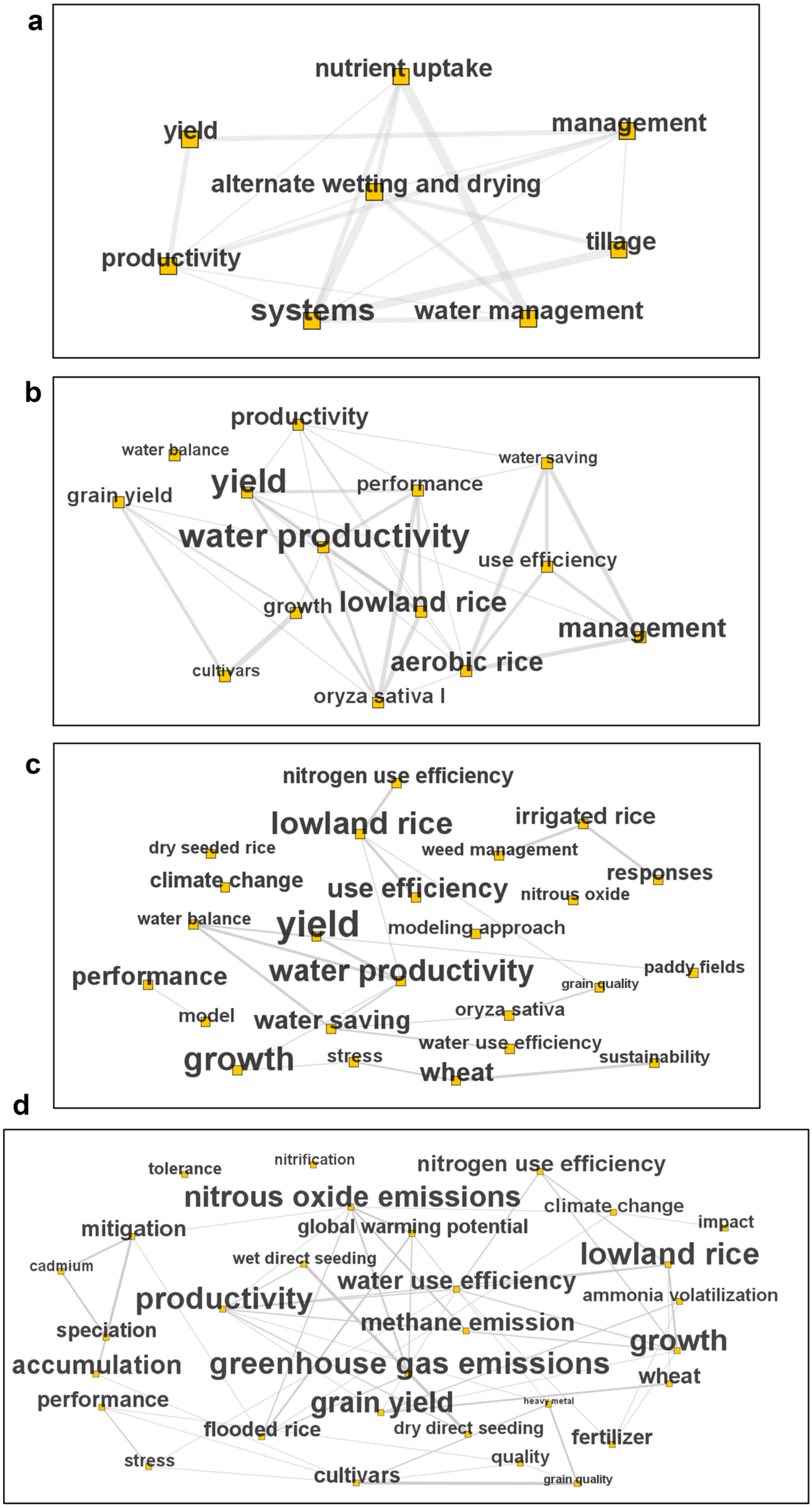
co-occurrence network, nodes represent keywords, and edges connect keywords that frequently appear together. The thickness of an edge reflects the strength of this connection—i.e. the frequency of co-occurrence. Similarly, the font size of each node corresponds to the keyword's frequency within the reference period. Keywords that commonly appear with many others occupy central positions in the network, indicating their relative importance.

The methodology involved a rigorous data cleaning process, excluding generic keywords to ensure the emergence of more focused and discipline-specific keywords. Using CiteSpace software, we analysed keyword networks from 2001 to 2021, divided into four five-year periods. This segmentation allows a detailed view of the discipline's evolving landscape, depicted in Fig. 2a–d, each illustrating the co-occurrence network for a specific period.

Beyond identifying the most relevant keywords for each period considered, we also evaluated bursts calculated using the CiteSpace software. A 'burst' in keyword frequency is a statistical assessment indicating a notable increase in occurrences within a specific time segment. This analysis divides the study period into smaller, consecutive segments. For each keyword, the software calculates the frequency in each segment and compares these across segments, identifying bursts where the frequency significantly exceeds the average in previous segments. This is achieved by evaluating the change in keyword frequency against a predetermined statistical threshold based on standard deviations from the mean frequency.

Over the years, some keywords such as 'yield', 'productivity', 'performance', 'lowland rice', and '*Oryza sativa*' consistently appear across all networks. Notably, 'yield' remains central, reflecting its importance both academically and in practical application, influencing farmers' adoption of AWD. 'Productivity' has been continuously explored, particularly focusing on water and land productivity to ensure

Fig. 2 **a** Keyword co-occurrence 2001–05, **b** Keyword co-occurrence 2006–10, **c** Keyword co-occurrence 2011–15, **d** Keyword co-occurrence 2016–21



sustainable cultivation. The performance of AWD in enhancing crop morphological and physiological features has also been a continual focus. The consistent presence of ‘lowland rice’ indicates the ongoing experiments in lowland environments and the comparisons with traditional management practices in these settings.

The first keyword co-occurrence network, shown in Fig. 2a, covers 2001–2005. Despite limited publications, early focus areas included ‘water management’, ‘yield’, and ‘systems’, and marked the start of formally defining ‘alternate wetting and drying’. ‘Management’ emerged as the keyword with the highest burst, as studies explored various water management techniques and land management challenges, indicating an initial focus on optimisation rather than environmental impacts. The keyword ‘nutrient uptake’ indicates early recognition of AWD’s impact on plant nutrition, while ‘tillage’ reflects interest in how soil management interacts with irrigation methods.

The second network (Fig. 2b) for 2006–2010 shows a strong focus on ‘yield’ and ‘water productivity’, with ‘yield’ experiencing the most significant burst, underscoring its centrality in AWD research. This period also introduces terms like ‘water saving’ and ‘use efficiency’, reflecting growing concerns about water scarcity. The keyword ‘cultivars’ highlights experiments testing the suitability of different cultivars under AWD conditions. The introduction of ‘aerobic rice’ aligns with AWD’s alternating aerobic and anaerobic conditions, particularly as it impacts arsenic accumulation in rice grains (Xu et al. 2008).

Figure 2c presents the network for 2011–2015, incorporating new concerns such as environmental impact and crop quality. For example, the consistent focus on yield’ and ‘water productivity’ is now interlinked with ‘nitrogen use efficiency’ and ‘climate change’, reflecting increasing concerns about the environment and nutrient management. Keywords like ‘nitrous oxide’ and ‘stress’ indicate a deeper investigation into the environmental impact of AWD and its effect on plant health and stress responses. This cluster also shows a noticeable trend towards investigating strategies and developing simulation models to enhance WUE and reduce environmental impact. Consequently, keywords such as ‘exploring options’, ‘modelling approach’, ‘model’, ‘water balance’, and ‘sustainability’ are prevalent.

The fourth network (Fig. 2d) for 2016–2020 marks a significant shift towards studying the environmental impacts of AWD, as shown by the emergence of keywords like ‘nitrous oxide emissions’, ‘greenhouse gas emissions’, ‘climate change’, ‘methane emission’, and ‘global warming potential’. Recent terms such as ‘ammonia volatilisation’ highlight a nuanced approach to nutrient management within AWD systems. Additionally, ‘grain quality’ and ‘quality’ link to consumer health and marketability, stressing the importance of maintaining or enhancing product quality. Lastly, the appearance of keywords such as ‘cadmium’, ‘accumulation’, and ‘heavy metal’ underscores new concerns about food safety and the risk of toxic metal accumulation in crops.

Co-citation analysis

Co-citation analysis is useful for outlining the foundational literature and identifying well-established trends in AWD research. This method extends beyond merely examining the papers in our database; it includes all documents cited within the body of AWD scientific literature. In a co-citation relationship, two or more papers are linked when other documents cite them together.

Figure 3 displays the co-citation network, representing only the 100 most cited documents. Each frame within the figure represents a cited document, colour-coded by their cluster affiliation. The size of each frame indicates the citation frequency, with larger frames highlighting the most cited articles within the AWD literature. Lines connecting the documents signify co-citation links, where each line’s thickness reflects the relationship’s strength.

Documents frequently cited together are positioned closely within the network, indicating strong thematic ties. Although there is some residual heterogeneity in how documents are distributed across different clusters, the co-citation analysis can effectively identify the core themes driving AWD research.

Cluster 1 (green)-water use, yields and water productivity Within the co-citation network, the first cluster gathers the highest number of citations. It is no coincidence that this cluster primarily comprises documents from 2000 to 2015, with many predating 2010. It focuses on the early development of AWD and other water-saving practices, some of which precede AWD’s formal introduction by IRRI in 2002. The central theme involves examining and validating irrigation solutions to reduce water use and enhance water productivity without significantly compromising yields. Key studies within this cluster include open-field research testing various strategies to curtail water consumption in rice farming. Examples include dry seeding (Tabbal et al. 2002), reducing ponded water depths (Bouman and Tuong 2001), and more or less advanced forms of AWD. Particular attention is paid to agricultural yields and water productivity.

The most cited paper by Bouman and Tuong (2001), predating the formalisation of AWD, explores multiple water-saving irrigation methods at the field level, including AWD. The authors express caution about the potential to maintain land productivity under these regimes and call for more research into enhancing yield potential and overall productivity. Similarly, Tuong et al. (2005) highlight the yield trade-offs associated with AWD, suggesting its impracticality and unattractiveness for farmers without complementary

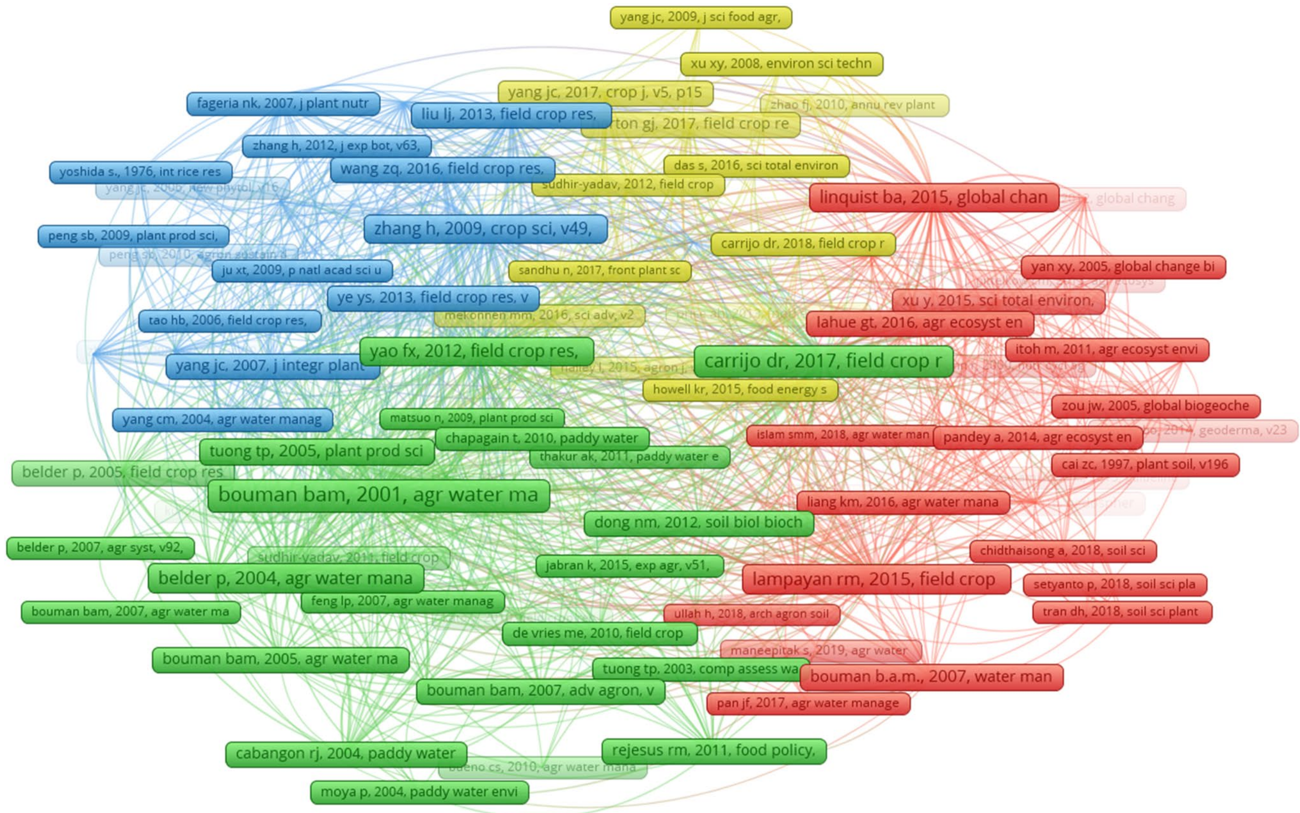


Fig. 3 Co-citation mapping

crop and resource management practices, such as germplasm selection and site-specific irrigation.

In contrast, Belder et al. (2004) and Cabangon et al. (2004) present findings where AWD did not significantly affect yields compared to CF, with the former noting increased water productivity under varying nitrogen fertilisation regimes. Moreover, the results of Cabangon et al. (2004) suggest that AWD can reduce agricultural water consumption without requiring different fertilisation regimes with respect to CF. According to Rejesus et al. (2011), findings from the Philippines indicate that AWD does not negatively affect the yields and profits of rice farmers. The study also emphasises the critical need for panel data to more accurately assess the impacts of AWD. Research by De Vries et al. (2010) in Senegal shows that an irrigation regime starting with CF and then switching to AWD could conserve water with minimal yield loss while maintaining low weed pressure and efficient use of N.

A 2017 meta-analysis by Carrijo et al. (2017) evaluated 56 studies for a total of 528 comparisons of irrigation regimes and found that AWD generally did not reduce yields under moderate conditions (i.e. soil water status threshold for re-flooding set at a sufficiently high soil water content), but led to significant losses under severe conditions. In particular, the study found that if the soil water status threshold is set by using a soil water tube, if the water level in the tube does not decrease below—15 cm from the soil surface before re-flooding the field, the yield loss is insignificant and the reduction in water use is around 23%. This highlights the potential to reduce water usage without affecting the yield when good plant development conditions are satisfied (Carrijo et al. 2017). In a study conducted by Yao et al. (2012), two rice varieties, a super rice variety and a drought-resistant rice variety, were evaluated under AWD and CF as the control group irrigation treatment. The results showed that while the yield differences between the two irrigation methods were insignificant, the super rice exhibited superior water productivity and nitrogen use efficiency under the AWD treatment compared to the CF control group.

Cluster 2 (red)–greenhouse gas emissions The papers in the second cluster (red) are more recent than those in the first one, and although the oldest was published in 1997, most of the documents were published during the last decade. The vast majority of papers in the second cluster, the largest for the number of publications, share a strong focus on the environmental impacts of rice cultivation, particularly regarding greenhouse gas emissions (GHG), such as methane and nitrogen oxides. These studies primarily consist of open-field research that explores the capacity of AWD and other water management regimes to mitigate GHG across various agricultural contexts and management systems. The significance of emissions from rice cultivation is underscored in both scientific and public discourse, given that rice is responsible for over 10% of global methane emissions and more than 30% in Southeast Asia, a major producer and consumer of rice (Pittelkow et al. 2013; Deininger 2022). Moreover, the global warming potential of rice farms is 169% higher than that of wheat and maise (Linquist et al. 2012).

A considerable volume of research in this cluster illustrates how AWD can effectively reduce greenhouse gas emissions, and help contain global warming (Zou et al. 2005; Sander et al. 2014; Linquist et al. 2015; Xu et al. 2015; Liang et al. 2016; Setyanto et al. 2018).

Linquist et al. (2015) assessed various AWD regimes (in duration and frequency) over two years at three different locations. The experiment examined several treatments: CF, AWD/40F, AWD/60, and AWD/40. Here, AWD/60 and AWD/40 denote the treatments where fields were flooded until the soil moisture level reached 60% and 40% of saturated volumetric water content, respectively. The AWD/40F treatment maintained similar conditions to AWD/40 but only until the plants reached the reproductive growth stage, after which the fields were continuously flooded until harvest. This study revealed that the AWD/40F treatment was the only one to maintain consistent yields across different treatments. Additionally, this method resulted in a 22% reduction in water usage and a significant 40% reduction in methane emissions, though it led to the highest arsenic concentration among all treatments. Conversely, the AWD/60 and AWD/40 treatments resulted in yield decreases of 5% and 13%, respectively, yet they were linked to a 93% reduction in methane emissions, increased water use efficiency by 40% and 63%, and a 56% lower arsenic accumulation compared to the CF treatment.

However, the dynamics are complex as drainage reduces methane emissions substantially but tends to increase nitrous oxide emissions, with the literature showing varied results depending on site-specific conditions. Xu et al. (2015) and Zou et al. (2005) found an 83% reduction in methane emissions but a 104% and 11% increase in carbon dioxide and nitrous oxide emissions, respectively. These changes illustrate the trade-offs between reducing methane and controlling other greenhouse gases. Despite the rise in carbon dioxide and nitrous oxide levels, the overall global warming potential and greenhouse gas intensity decreased by up to 25% and 29%, respectively, when using intermittent flooding compared to CF. On the other hand, Setyanto et al. (2018) observed no difference in yield but found a reduction of over 35% in methane emissions, with seasonal total nitrous oxide emissions remaining similar to CF. Sibayan et al. (2018) noted that while the total seasonal methane emission was significantly higher during the wet season compared to the dry season, AWD reduced methane emissions by only 1.7% compared to CF, and nitrous oxide emissions increased by 97%. Islam et al. (2018) analysed the effects of the timing and duration of drainage on GHG emissions in rice soils amended with residue, finding that early-season drainage combined with mid-season drainage could reduce methane emissions by up to 90%. The findings from these studies highlight that while methane emissions generally decrease with the adoption of AWD compared to CF, the results for nitrous oxide are mixed, indicating the need for further research to determine the factors influencing these outcomes.

Nalley et al. (2015) conducted a comprehensive analysis of various AWD regimes in Arkansas, showing that AWD can enhance water use efficiency by 21–56% while simultaneously reducing rice production's yield-scaled Global Warming Potential (GWP) by 45–90%. The yield-scaled GWP is a metric that measures the GWP per unit of yield, comparing the relative impact of different greenhouse gases based on their heat-trapping ability relative to carbon dioxide (van Groenigen et al. 2010). The significant reduction in GWP noted in this study is primarily due to decreased methane emissions facilitated by AWD practices. Moreover, the research highlights the economic viability of AWD irrigation beyond its environmental benefits, as it leads to considerable savings in water and energy expenses. The study also points out potential improvements in grain quality under AWD conditions, which could fetch higher market prices and increase farmer profits. Reflecting on water-saving, productivity, and economic profitability, Lampayan et al. (2015) demonstrated that appropriate AWD implementation could reduce water use by an average of 38% without compromising yield. This study extended beyond technical assessments to examine the economic impact on farmers' net income, which was found to increase by 38% in Bangladesh, 32% in the Philippines, and 17% in Vietnam, primarily due to reduced water pumping and fuel expenses. The success of these practices hinges on close collaboration with extension services and robust farmer groups to disseminate and validate new technologies. Crucially, for widespread adoption, these practices must be economically appealing and adaptable to local conditions (Linquist et al. 2015).

Cluster 3 (blue)-agronomic, morphological and physiological response The documents in the third cluster exhibit a thematic overlap with the first one, with documents primarily derived from experimental studies exploring the responses of rice cultivation to dry conditions (Bouman 2007; Liu et al. 2013; Matsuo and Mochizuki 2015). Unlike the first cluster, which focuses on the potential of AWD for enhancing yields, water savings, and water productivity, the documents in the third cluster predominantly examine rice's morphological and physiological responses to various irrigation regimes and agronomic conditions.

Several studies within this cluster address topics such as root and shoot growth under AWD conditions (Yang et al. 2004; Zhang et al. 2009; Kato and Okami 2010). Other investigations explore the morphological and physiological traits of roots and shoots (Chu et al. 2014), root-soil interactions (Zhang et al. 2012), and the role of cytokinins in grain filling (Zhang et al. 2010). One particular study by Zhang et al. (2009) highlights that, compared to CF conditions, a mild AWD regime significantly enhances root oxidation activity, increases cytokinin concentrations in roots and shoots, boosts the photosynthetic rate in leaves, and elevates the activity of key enzymes involved in the conversion of sucrose to starch in grains. This study found that the grain yield of the two rice varieties tested was increased by an average of 11%, while their WUE improved by 55%. The authors conclude that a moderate wetting and drying regime can significantly promote root growth, which in turn benefits other physiological processes, ultimately leading to higher grain yield and improved WUE.

Moreover, Fageria (2007) discusses the impact of various stresses on growth and yield formation throughout the rice growth cycle, noting that the reproductive stage is most susceptible to biotic and abiotic stresses, followed by the spikelet filling and vegetative stages. This study underscores the critical importance of understanding the morphological and physiological responses of rice to different irrigation regimes, particularly during the reproductive phase, which is pivotal for achieving higher yields.

Cluster 4 (yellow)––rice grain health The fourth cluster introduces critical issues related to the health of rice grains within the AWD literature, focusing on contaminants like arsenic accumulation (Carrijo et al. 2018), cadmium (Yang et al. 2009), and the enhancement of essential dietary micronutrients in harvested rice grains (Price et al. 2013). Extensive research indicates that AWD, and more broadly, aerobic rice conditions, can significantly reduce the accumulation of arsenic in harvested rice grains. For instance, Carrijo et al. (2018) documented that arsenic levels in grains could be reduced by up to 68% under the driest AWD conditions. This finding aligns with other studies, such as that by Xu et al. (2008), which reported arsenic concentrations in rice to be 10–15 times higher under CF compared to AWD. The increased bioavailability of arsenic under flooded conditions likely contributes to this disparity (Takahashi et al. 2004; Xu et al. 2008).

In a comprehensive two-year study conducted in Bangladesh, Norton et al. (2017) evaluated field production, grain quality, and concentrations of heavy metals such as arsenic and cadmium under both safe AWD and CF irrigation regimes. Their findings revealed that heavy metal accumulation in grains varied depending on the heavy metal considered. Specifically, arsenic levels in rice were reduced by 13.7% and 25.7% compared to CF across the two study years. Conversely, cadmium concentrations were higher under AWD, increasing by 27.8% in 2013 and 67.3% in 2014. Although these increases were substantial, the actual cadmium levels in the grains remained below the safety thresholds established by Bangladesh legislation. The literature generally suggests that cadmium behaves differently from arsenic, increasing under more aerobic soil conditions. However, some studies report contrary findings. For example, Yang et al. (2009) explored two AWD regimes characterised by moderate and severe soil water statuses. Their results showed that the moderate regime decreased cadmium content in the grain by 19–21% and in milled rice by 40%, while the more severe regime increased cadmium levels in the grain but reduced it in milled rice compared to CF. These complex interactions highlight the need for further research to explain the factors influencing the reduction of cadmium concentrations in rice grains under aerobic conditions.

Conclusions and perspectives

This study analyses 439 scientific articles published over a thirty-year period, illuminating the increasing prominence of AWD in academic publications. Since the 1990s, the importance of AWD has grown significantly, with a notable peak in the last 5 years. This trend suggests that the full potential of AWD is yet to be realised and explored. The majority of the research originates from Oriental countries, with the USA and Australia ranking as the second and fifth most productive countries, respectively.

The analysis of keyword trends in AWD research reveals a consistent focus on certain themes over the years while also showing a clear evolution in the topics addressed. Co-citation analysis within the AWD literature has provided valuable insights into the research structure, tracing the relationships between citations to outline the various research strands and identifying key publications that have shaped the field over the years.

Historically, research primarily concentrated on optimising productivity and agricultural yields and evaluating different irrigation regimes aimed at enhancing rice production performance through AWD. However, over time the scope of research has broadened to include health-related and environmental issues, reflecting a larger trend in agriculture and research towards sustainable and environmentally responsible practices. Researchers are increasingly investigating the potential health impacts, such as heavy metal accumulation in rice grains and dietary exposure to consumers, as well as the environmental impacts of AWD, particularly regarding climate-altering gas emissions and effects on surface and groundwater quality.

Additionally, AWD research is exploring innovative areas such as the impact of AWD on organically produced rice (Islam et al. 2020) and the use of modelling techniques to extrapolate findings from individual experiments to broader geographic areas (Shekhar et al. 2020, 2021; Gilardi et al. 2023). The economic sustainability of AWD adoption is also a growing focus of study (Alauddin et al. 2020; Hao et al. 2022; Poddar et al. 2022). Moreover, AWD research is extending beyond traditional regions like Asia, the USA, and Australia to places like the Mediterranean basin (Monaco et al. 2021; Gharsallah et al. 2023; Gonçalves et al. 2022; Gilardi et al. 2023), where AWD is being evaluated as a viable technique to address local issues while maintaining traditional gravity irrigation systems.

It is important to stress that bibliometric analysis presents several limitations that are important not to overlook for the sake of the study's transparency. The completeness of the database is influenced by the period considered and the exclusion of non-English papers, books, proceeding papers, and grey literature, potentially omitting significant trends. Additionally, the quality of analysed research may be impacted by publication biases, which preferentially publish findings based on perceived novelty or impact. The inclusion of self-citations can artificially inflate citation counts. Moreover, bibliometric analysis primarily focuses on quantitative rather than qualitative data, highlighting the need for inputs from multidisciplinary research groups to assess the quality of contributions and extract key messages.

This bibliometric analysis provides valuable insights for several stakeholders, including researchers, policymakers, and practitioners. For researchers, the analysis offers a comprehensive overview of the current state of AWD research, highlighting key focus areas, influential publications, and prominent authors. This resource is invaluable for those new to the field or looking to deepen their understanding of specific aspects of AWD. For resource managers and policymakers, the findings identify gaps in current research, aiding in the prioritisation of further investigation to advance AWD practices. Lastly, the analysis offers insights into the main advantages and most effective methods for farmers interested in implementing AWD systems, supporting better-informed decision-making in agricultural practices.

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Declarations

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