ISSN: 1411-5719(p): 2655-500X (e),
Volume 23 No. 01 (June 2026): 60-70

Soil and Water Journal
Jurnal Tanah dan Air

RESEARCH ARTICLE OPEN ACCESS

AGRICULTURAL METHANE REDUCTION THROUGH ALTERNATE WETTING AND DRYING: A BIBLIOMETRIC ANALYSIS

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ABSTRACT

Article History :
Received: 2026-01-04
Revised: 2026-01-25
Accepted: 2026-06-02
Published: 2026-08-15
DOI : 10.31315/jta.v23i1.16332

Methane emissions from the agricultural sector represent a critical challenge for global climate change mitigation. This study aims to map the patterns, trends, and development of research on methane emission reduction in the agricultural sector through the implementation of Alternate Wetting and Drying (AWD) using a bibliometric approach. Scientific publication data were collected from Scopus and analyzed following the PRISMA method, resulting in 325 relevant articles for analysis using VOSviewer. The results reveal a significant increase in publications, particularly after 2021, and identify five main thematic clusters ranging from biophysical responses to environmental quality. Temporal analysis indicates a shift in research focus from biophysical approaches toward the integration of climate mitigation, resource-use efficiency, and sustainable agricultural systems. This study concludes that AWD is an effective mitigation strategy with strong potential to reduce methane emissions without compromising rice productivity. Ultimately, these findings underscore the necessity of integrating AWD into future sustainable agricultural policies and climate mitigation actions to advance low-carbon food production globally.

Keywords: Alternate wetting and drying, bibliometric analysis, low-carbon agriculture, methane emission reduction, sustainable agriculture

How to cite:
Amanda, M. A. & Amalia S. R. 2026. Agricultural Methane Reduction Through Alternate Wetting and Drying: A Bibliometric Analysis. Soil and Water Journal. 23(01): 61-71. DOI: 10.31315/jta.v23i1.16332.

INTRODUCTION

Irrigated rice cultivation plays a crucial role in ensuring global food security, with approximately 93 million hectares of irrigated paddy fields contributing to 75% of global rice production. However, this system consumes about 40% of the world's total irrigation water, making the rice agricultural sector a major contributor to freshwater scarcity pressure (Pandey et al., 2010). This condition is further exacerbated by climate change, water pollution, deteriorating irrigation infrastructure, and increasing competition for water from domestic and industrial sectors. Therefore, innovation in water management is imperative to maintain the long-term sustainability of global food production (Lampayan et al., 2015)

On the other hand, the flooded paddy systems that characterize conventional rice cultivation are also significant sources of greenhouse gas emissions, particularly methane (CH_4) (Mariani & Ferrante, 2017). Anaerobic processes in continuously waterlogged paddy environments drive microbial methane formation, which substantially contributes to global warming and climate instability. Given the high urgency of reducing agricultural sector emissions in the global climate change agenda, low-emission rice cultivation practices are increasingly required to achieve carbon neutrality goals (Ishfaq et al., 2020).

In response to these environmental challenges, Alternate Wetting and Drying (AWD) has emerged as a landmark water management technology that offers a dual solution: improving water use efficiency while simultaneously mitigating methane emissions. AWD applies periodic cycles of flooding and soil drying, in which irrigation is resumed when the groundwater level reaches a certain depth, commonly around 15 cm below the soil surface to avoid water stress in rice plants. This approach can reduce irrigation water requirements by 10-40%, increase grain yields by approximately 10% and lower greenhouse gas (GHG) emissions by 45-90% compared with continuous flooding (Lampayan et al., 2015).

In addition to its environmental and productivity benefits, AWD has the potential to provide additional advantages, including reduced accumulation of toxic heavy metals such as arsenic and cadmium in rice grains, as well as lower energy consumption, particularly in pump-based irrigation systems. Consequently, AWD practices have become an increasingly important component of carbon credit methodologies and sustainable carbon market frameworks for rice cultivation in several developing and developed countries (Montzka et al., 2011).

Although the potential of this technology is widely recognized worldwide, the adoption of AWD remains uneven across major rice-producing regions. This limited implementation is heavily influenced by agroecological variability, farmers' uncertainty regarding potential yield reductions and the limited availability of reliable groundwater-level monitoring devices at the farm level. Yield variability across different geographic locations and lingering uncertainty in localized implementation guidelines reported in several foundational studies highlight the need for more in-depth, targeted, and consolidated research efforts (Bouman et al., 2007).

Given the importance of AWD in the transition toward sustainable and low-emission agriculture, mapping global research on this topic represents a strategic step. This study aims to map patterns, trends, and the development of research on methane emission reduction in the agricultural sector through the implementation of Alternate Wetting and Drying (AWD) using a bibliometric approach. Such mapping will help identify trends in knowledge development, international research collaboration, wellstudied aspects such as crop yield and water use efficiency, as well as underexplored areas including social adoption factors and economic impacts. With this understanding, future research and policies can be more effectively directed to support the implementation of AWD as a climate change mitigation solution in the agricultural sector (Lampayan et al., 2015).

MATERIALS AND METHODS

This study adopts the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure a rigorous and structured literature selection process. The methodology encompasses a systematic multi-stage workflow, including record identification, screening, eligibility assessment, data extraction, and comprehensive synthesis. Applying bibliometric analysis to conduct a meta-literature review is an emerging approach. Unlike conventional statistical meta-analyses that rely on the regression of empirical data, this study integrates bibliometric network mapping with content analysis of the Alternate Wetting and Drying literature.

This study integrates quantitative bibliometric mapping with qualitative thematic interpretation within a systematic literature review framework. Quantitative techniques were applied to visualize publication trends, collaboration networks, and keyword co-occurrences, while qualitative analysis was conducted to interpret dominant research themes and their temporal evolution. Literature data were retrieved from the Scopus database due to its comprehensive coverage of peer-reviewed international journals. The search was restricted to articles published between 2016 and 2025 to capture recent developments in AWD research and its alignment with low-carbon agriculture and climate change mitigation. All retrieved records were screened to ensure relevance, authenticity, and consistency.

To ensure methodological rigor, all analyzed articled underwent a structured systematic selection process adapted from Paltrinieri et al. (2023) and Nasir et al. (2023). All materials were selected based on their relevance to the analyzed topic within the Scopus database. The literature search was initiated using the search term "Alternate Wetting and Drying" which initially yielded 1,350 documents, excluding book chapters, conference proceedings, and non-refereed items. The subsequent phase (stage two) involved these 1,350 records. To maintain high literature quality, only articles published in Scopus-indexed Q1 and Q2 journals were retained. Additionally, studies irrelevant to Alternate Wetting and Drying or those with duplicate content were removed. The third stage involved assessing the eligibility of the remaining articles that passed the initial screening. The fourth stage evaluated document accessibility, retaining only full-text available articles. Following this four-stage PRISMA-guided selection process, 325 articles were finalized for bibliometric analysis.

The analysis utilized VOSviewer software (van Eck & Waltman, 2010) to visualize and map bibliometric networks across the selected publications. The analytical framework encompassed three main techniques: co-authorship analysis to map research collaborations, co-citation analysis to evaluate foundational works, and keyword co-occurrence analysis to examine thematic structures. Specifically, co-authorship analysis identified the most productive authors and key institutional networks advancing AWD and rice water management literature. Co-citation analysis highlighted influential publications that have shaped the intellectual foundation of the field. Finally, keyword co-occurrence mapping revealed underlying thematic clusters and emerging research priorities. Collectively, these integrated bibliometric approaches provide a comprehensive overview of the field's intellectual structure and evolving trends (Ali et al., 2024; Qosim et al., 2023).

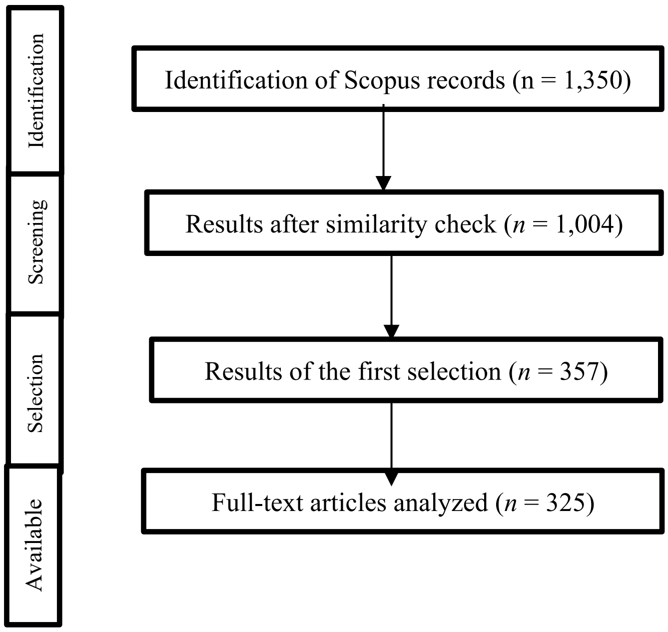

Figure 1. PRISMA search strategy

Figure 1 illustrates the PRISMA-based literature selection process implemented in this study, detailing the four sequential stages of identification, screening, eligibility, and final inclusion. As depicted, the initial search in the Scopus database yielded 1,350 records, which were reduced to 1,004 following a deduplication and similarity check. Subsequent screening and quality filtering restricted, strictly to Scopus Q1 and Q2 journals, narrowed the selection to 357 articles. After evaluating full-text accessibility, a final dataset of 325 articles was retained for bibliometric analysis. This systematic refinement ensures both dataset relevance and methodological rigor.

RESULTS AND DISCUSSION

A comprehensive evaluation of the 325 selected articles reveals the thematic development and intellectual landscape of Alternate Wetting and Drying (AWD) research. Figure 2 displays the keyword co-occurrence network map generated via VOSviewer to identify the primary research clusters.

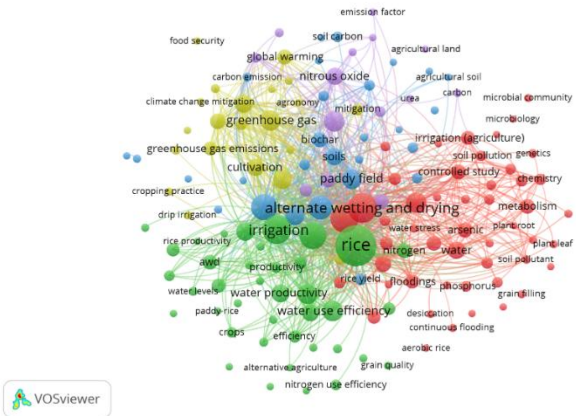

Figure 2. Identification of keywords in the literature Alternate Wetting and Drying

Bibliometric mapping using VOSviewer identifies five major interconnected thematic clusters in AWD research (Figure 2). The keywords alternate wetting and drying, rice, irrigation, and paddy field form the central nodes, confirming that paddy water management is the dominant mitigation focus, consistent with evidence that continuously flooded systems create anaerobic conditions that favor methanogenesis (Bouman et al., 2007; Wassmann et al., 2010).

Cluster 1 (Red) AWD, Water, and Plant Biological Responses. Centered on keywords such as rice, water, nitrogen, flooding, and root metabolism, this cluster covers the physiological responses of rice to changing water regimes. AWD shifts soil redox conditions from anaerobic to semi-aerobic, suppressing methanogenesis and, within a safe drying threshold, enhancing root growth and nitrogen uptake (Bouman et al., 2007; Lampayan et al., 2015).

Cluster 2 (Green) Water Efficiency and Rice Productivity. Dominated by keywords such as irrigation, water use efficiency, water productivity, and rice yield, this cluster frames AWD as delivering water savings alongside stable yields. Applying the "safe AWD" threshold, resuming irrigation once the water table drops to about 15 cm below the soil surface can cut irrigation water use by 10-40% without reducing productivity (Lampayan et al., 2015). Reflecting a shift from proof-of-concept toward farm-level application.

Cluster 3 (Yellow) Greenhouse Gas Emissions and Climate Change Mitigation. Encompassing greenhouse gas, methane emission, global warming, and climate change mitigation, this cluster positions AWD directly within climate policy. AWD implementation can lower methane emissions by 30-90% compared with continuous flooding, substantially reducing the global warming potential of rice systems (Linquist et al., 2015) reframing AWD from a water-saving technique into a climate mitigation strategy.

Cluster 4 (Blue) Soil, Carbon, and Nitrogen Cycles. Centered on soil carbon, nitrous oxide, urea, and biochar, this cluster examines AWD's biogeochemical trade-offs. Although AWD can increase N_2O emissions during the aeration phase, the much larger reduction in CH_4 still lowers total global warming potential, while improved nitrogen use efficiency reduces losses through percolation and denitrification when combined with proper fertilizer management (Bouman et al., 2007; Yang & Zhang, 2010)

Cluster 5 (Purple) Environment, Soil Pollution, and Food Safety. Highlighting arsenic, soil pollution, and microbial community, this cluster reflects AWD's co-benefits for environmental quality and food safety: the more aerobic soil conditions it creates limit arsenic solubility and reduce grain accumulation of arsenic and other heavy metals (Nalley et al., 2015), extending AWD's relevance beyond water and emissions into public health and sustainable development.

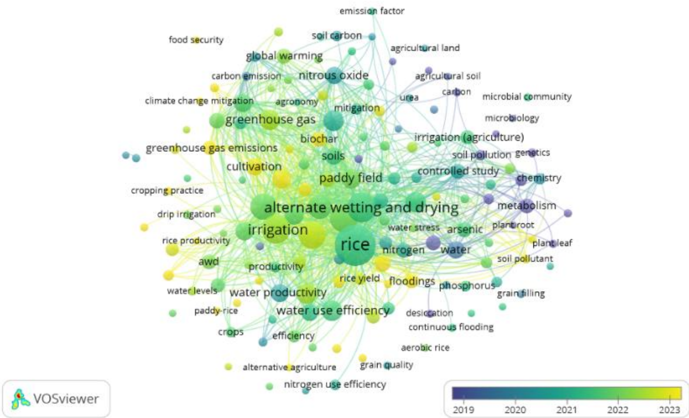

Figure 3. Identification of the words Alternate Wetting and Drying in the year

Earlier keywords representing blue and green clusters, such as soil carbon, nitrous oxide, and nutrient cycling, reflect a foundational focus on biogeochemical mechanisms, particularly the trade-off between methane reduction and potential N_2O increases (Bouman et al., 2007; Yang & Zhang, 2010). In contrast, more recent keywords highlighted in yellow including water use efficiency, rice yield, and climate change mitigation mark a shift toward applied and impact-oriented research. These studies confirm that AWD reduces irrigation water requirements by 10-40% and methane emissions by up to 90% without compromising grain yield (Lampayan, Samoy-Pascual, et al., 2015; Linquist et al., 2015). Additionally, the recent emergence of terms like arsenic and soil pollution signals AWD's expanding relevance to broader environmental quality and food safety concerns (Nalley et al., 2015).

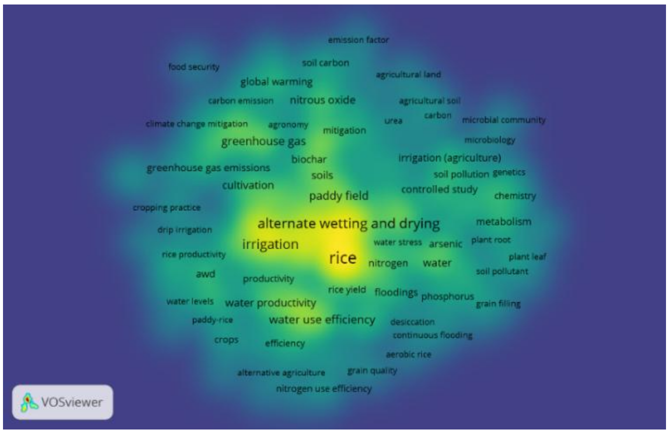

Figure 4. Visualization of Alternate Wetting and Drying Publication Density

The Density Visualization (Figure 4) confirms that research intensity is highest around rice, alternate wetting and drying, irrigation, and water use efficiency, reinforcing paddy water management as the dominant mitigation pathway. Medium-density topics, including nitrogen, nitrous oxide, soil carbon, and biochar indicate that nutrient cycling and N_2O trade-offs remain active but secondary concerns (Yang & Zhang, 2010). Lower-density topics such as grain quality, microbiology, and soil pollutants represent clear opportunities for further research, particularly on the long-term effects of AWD on crop quality and soil microbial dynamics.

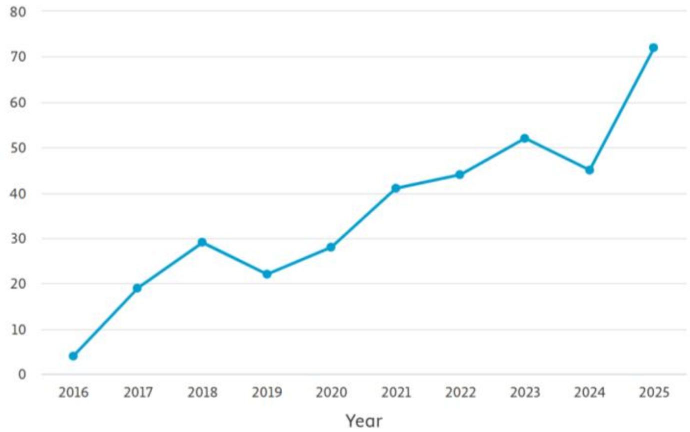

Figure 5. Growth of Alternate Wetting and Drying publications in the year

The number of AWD-related publications grew steadily over 2016-2025 (Figure 5). Early growth (2016-2018) reflects rising concern over water scarcity and the recognition of AWD as a water-saving practice capable of maintaining yields while reducing methane emissions (Bouman et al., 2007; Lampayan et al., 2015; Linquist et al., 2015). Publications fluctuated moderately in 2019-2020 as research broadened from agronomic performance toward greenhouse gas mitigation and climate adaptation, before surging sharply in 2021-2023, consistent with strengthening international commitments to low-carbon agriculture and the inclusion of rice cultivation in national climate action plans and carbon credit schemes (Montzka et al., 2011). After a slight dip in 2024, publications rebounded sharply in 2025, indicating that AWD research has evolved from a localized technical topic into a multidisciplinary global agenda supporting sustainable agriculture, food security, and climate change mitigation.

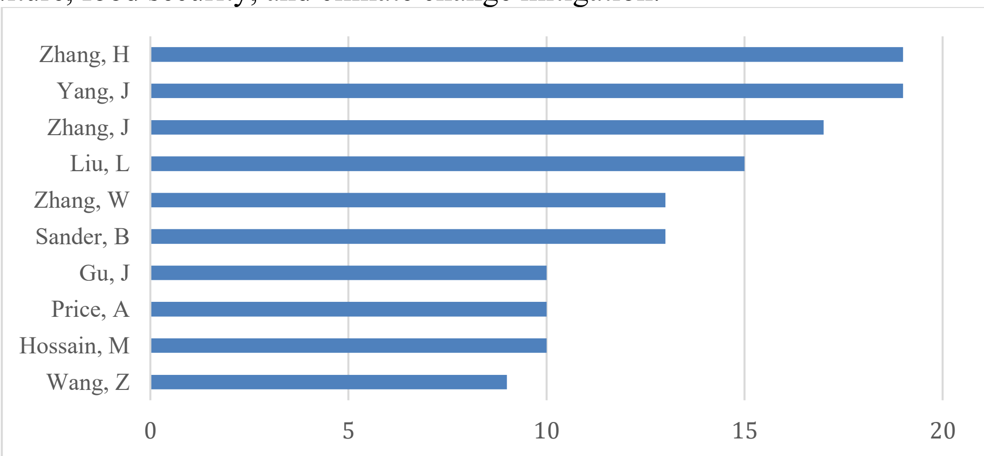

Figure 6. Influential authors in the Alternate Wetting and Drying literature

Bibliometric analysis of author productivity shows that AWD research is led by a core group of researchers spanning agronomy, plant physiology, and irrigation optimization (Figure 6). Zhang, H. and Yang, J. rank highest with 19 publications each, followed by Zhang, J. (17) on land management and greenhouse gas issues, and Liu, L. (15) on soil mechanisms and nutrient cycling. Zhang, W. and Sander, B. (13 each) contribute through emission modeling, while Gu, J., Price, A., and Hossain, M. (10 each) and Wang, Z. (9) reflect active involvement across diverse rice-producing agroecological zones. This diversity underscores the collaborative, multidisciplinary nature of AWD research, bridging plant science and environmental policy.

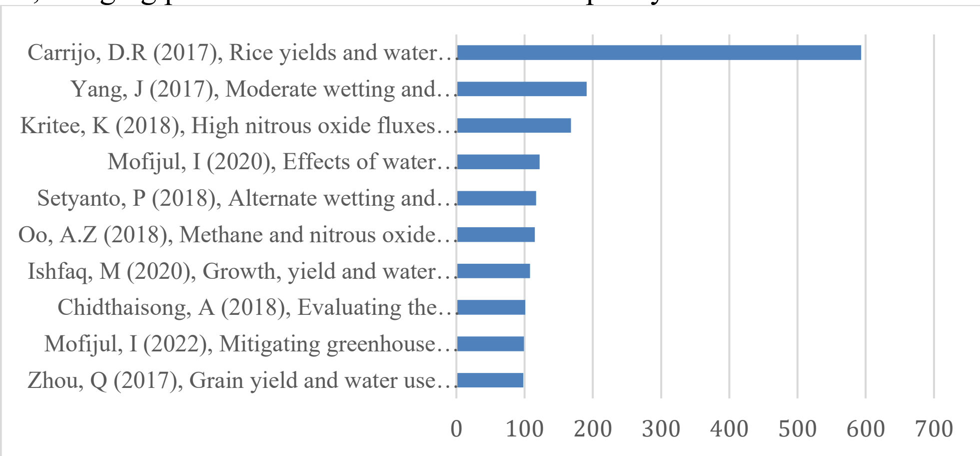

Figure 7. The most influential articles in the Alternate Wetting and Drying literature

Citation analysis shows that AWD research has been shaped by several highly cited works (Figure 7). The most influential is Carrijo, D.R. (2017), 'Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis,' with 593 citations, providing robust meta-analytic evidence that AWD saves irrigation water without reducing yields and establishing much of the field's empirical foundation. Yang, J. (2017), with 191 citations, introduced 'moderate' AWD, showing that it can raise yields and water use efficiency while also lowering methane emissions and arsenic accumulation in grain. Kritee, K. (2018) with 168 citations offers a critical counterpoint, showing that poorly managed AWD can increase N_2O emissions even as methane is suppressed, underscoring the need to balance CH_4 and N_2O jointly. Field-based studies from developing countries reinforce these findings: Mofijul, I. (2020, 122 citations) and Mofijul, I. (2022, 99 citations) show that combining AWD with efficient fertilizer management lowers total emissions without sacrificing productivity in Bangladesh, while Setyanto, P. (2018, 117 citations) confirms AWD's effectiveness in Indonesian paddy fields. Further evidence from Oo, A.Z. (2018) and Chidthaisong, A. (2018), complemented by Ishfaq, M. (2020) and Zhou, Q. (2017), confirms that AWD can be applied across diverse rice cultivation systems while maintaining or enhancing productivity.

Table 1. Most influential countries in the literature on Alternate Wetting and Drying

Country	Document
China	112
United States	54
Philippines	33
Bangladesh	31
Japan	30
India	25
Germany	22
United Kingdom	21
Thailand	19
Australia	18

Bibliometric analysis shows that AWD research is dominated by countries with extensive rice farming systems and strong interests in water management and greenhouse gas mitigation (Table 1). China leads with 112 documents, reflecting its central role in developing and testing AWD amid vast paddy fields and high irrigation demand. The United States ranks second (54 documents), contributing mainly through emissions modeling, methodological development, and policy analysis rather than large-scale cultivation. Major Asian rice producers including the Philippines (33), Bangladesh (31), Japan (30), and India (25) show strong involvement reflecting AWD's strategic importance for regional water and climate agendas, from field-level adoption studies to responses to declining groundwater tables. In Europe, Germany (22) and the United Kingdom (21) integrate AWD into sustainable agriculture and climate policy research, while Thailand and Australia link it to national adaptation and irrigation-efficiency programs.

Table 2. Influential journals in the Alternate Wetting and Drying literature

Journal	Document
Agronomy	29
Agricultural Water Management	24
Water (Switzerland)	14
Sustainability (Switzerland)	13
Journal of Integrative Agriculture	12
Food and Energy Security	11
Frontiers in Plant Science	11
Soil Science and Plant Nutrition	9
Agriculture (Switzerland)	9
Field Crops Research	8

Publications on AWD are distributed across reputable international journals spanning agronomy, water management, environment, and food security (Table 2). Agronomy leads with 29 publications, reflecting AWD's framing as an agronomic innovation for enhancing water use efficiency without compromising yield, followed by Agricultural Water Management (24), which emphasizes irrigation performance and water productivity. Water (Switzerland, 14) and Sustainability (Switzerland, 13) reflect AWD's expansion into resource management and the Sustainable Development Goals, while the Journal of Integrative Agriculture (12) and Food and Energy Security (11) highlight the food-water-energy nexus. Frontiers in Plant Science and Soil Science and Plant Nutrition (11 and 9) explore plant-physiological and soil-nutrient dimensions, and Agriculture (Switzerland, 9) and Field Crops Research (8) provide applied, field-based evidence. Together, this spread confirms that AWD research has matured into a multidisciplinary field.

CONCLUSION

Bibliometric analysis confirms that Alternate Wetting and Drying (AWD) is an effective paddy water management strategy for reducing methane emissions while improving water use efficiency and maintaining rice productivity. Publications have grown rapidly since 2021, and research themes have shifted from biophysical mechanisms toward integrative perspectives covering productivity, greenhouse gas mitigation, and environmental quality. These findings support wider policy adoption of AWD through irrigation management programs, climate mitigation strategies, and carbon credit schemes for sustainable rice cultivation.

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