GLOBAL TRENDS AND KNOWLEDGE MAPPING OF WHEAT WATER–FERTILIZER COUPLING STUDIES: A QUANTITATIVE ANALYSIS OF RESEARCH OUTPUTS FROM 2000 TO 2024

HAN, Y. Y – HU, M. H. – TONG, L. C. – JING, A. H. – YE, Y. H.*

College of Forestry and Grassland, Xizang Agriculture and Animal Husbandry University, Nyingchi, Tibet, China

**Corresponding author*
e-mail: yeyanhui@xza.edu.cn

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Abstract. *Triticum aestivum L.* is a key global staple crop, and coupled water–fertilizer management enhances its productivity and resource efficiency. Although narrative reviews are available, large-scale bibliometric analyses are scarce. This study used bibliometrics to analyze 3193 Web of Science Core Collection publications (2000-2024) on wheat water–fertilizer coupling. Annual publications showed an increase with China and the U.S. contributing significantly. Major journals included Field Crops Research and Agricultural Water Management. Major keywords, such as “management” and “yield” reflected core goals of improving efficiency and productivity. Key directions include water–fertilizer synergistic mechanism analysis and precise technological application. Recent hotspots encompass physiological/metabolic regulation, the molecular genetic basis of nutrient use, intelligent decision models, and microbial fertilizer synergism. The study organizes the theoretical framework and technical pathways , offering a basis for efficient water–fertilizer use, green high-yield cultivation, and agricultural sustainability.
Keywords: *Triticum aestivum L., water–fertilizer coupling, regulatory mechanisms, yield increase, bibliometrics*

Introduction

Global climate change and rapid population growth are exerting increasing pressure on agricultural systems, particularly in terms of water scarcity and food security. As a basic natural resource for ecosystem balance and human survival and development , the scarcity of water resources is particularly prominent in the field of agriculture (Wang et al., 2022b). According to authoritative data, in 2019, the total water consumption of agriculture in 180 major countries or regions worldwide reached 2.90×10^{12} m^3, accounting for 71.49% of the total global water consumption (Wada and Bierkens, 2014). This data reflects the widespread waste and inefficient use of water resources in agricultural production. The reason for this is that the roughness of traditional irrigation methods, the lag in updating irrigation technology, and the imperfections of water resource management mechanisms have jointly led to a large loss of water resources in the process of transmission, distribution and use. At the same time, fertilizer, as a core element to ensure stable and increased agricultural production, has become an increasingly serious environmental problem caused by its irrational application. In order to pursue higher crop yields, the phenomenon of excessive fertilizer application is spreading globally. in 2020, the total amount of agricultural nitrogen fertilizer used in 164 major countries or regions reached 1.13×10^8 t (Menegat et al., 2022). Excessive irrigation and fertilization not only failed to achieve the expected yield increase, but also triggered a series of chain reactions. At the soil level, the problem of soil salinization has

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intensified, destroying the soil structure and microbial community balance; in the water environment, a large amount of nitrogen, phosphorus and other nutrients that are not absorbed by the crop enter the water body along with the surface runoff and underground seepage, resulting in the pollution of groundwater and surface water, and triggering ecological crises, such as eutrophication; in the field of the atmospheric environment, the over-application of nitrogen fertilizers leads to the leaching of nitrate, which generates a large amount of greenhouse gas emissions (Yang et al., 2017). In 2021, N_2O emissions from fertilizer application in 95 major countries or regions amounted to 1,652,500,000 t, which is converted to CO_2 equivalent emissions of about 438 million t. Among them, N_2O emissions from four countries, namely, China, India, the United States and Brazil, totaled 948,800,000 t, and China ranked the first with 377,900,000 t, which undoubtedly brings a great pressure (Hassan et al., 2022).

In response to mounting challenges in agricultural water and fertilizer management, water–fertilizer integration has emerged as a pivotal technology for advancing sustainable crop production (Grafton and Yule, 2015). This technology precisely dissolves soluble fertilizer in irrigation water, and with the help of advanced irrigation systems, water and nutrients are directly transported to the roots of crops, which greatly reduces the ineffective loss of water and nutrients in the transport process. From the perspective of crop growth, water and fertilizer integration can provide more appropriate water and fertilizer supply for crops to meet the needs of their different growth stages, effectively promote crop growth and development, and then achieve crop yield and fruit quality improvement. In terms of water saving and fertilizer saving, compared with traditional irrigation and fertilizer application methods, water and fertilizer integration technology can save 30%-50% of water and 20%-30% of fertilizer (Lakhiar et al., 2024). Compared with conventional irrigation and fertilization approaches, this technology has been shown to reduce water use by 30–50% and fertilizer input by 20–30%, while simultaneously mitigating environmental pollution caused by nutrient runoff and excessive chemical application.

Crop water and fertilizer integration technology can be traced back to Israel in the 1950s (Tal, 2016). As an arid water-scarce country, Israel, with scientific and technological innovation, vigorously develops micro-irrigation technology, including drip irrigation (drip irrigators and drip irrigation belts), micro-sprinkler irrigation and subsurface drip irrigation and other forms, of which drip irrigation water–fertilizer integration and under-film drip irrigation water–fertilizer integration are the most widely used. With advanced technology and perfect promotion system, Israel's drip irrigation area accounted for more than 85% of the total irrigated area, which has become a global model for the application of water–fertilizer integration technology (Fishelson and Rymon, 1989). The United States also attaches importance to the development of water–fertilizer integration technology, and from 2003 to 2015, its drip irrigation area achieved a remarkable growth of 75%, expanding from 600,000 hm^2 to 1.05 million hm^2 (Thompson et al., 2009). China has been involved in research on water–fertilizer integration-related topics since the 1970s, and after years of technology research and development, demonstration and promotion, and policy support, as of the end of 2020, the area of water–fertilizer integration technology promotion has exceeded 10 million hm^2, and has driven the application of more than 13.33 million hm^2 of surrounding farmland, which has played an important role in guaranteeing the national food security and agro-ecological security (Yang et al., 2024).

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Although scholars around the world have carried out a large number of studies on crop water–fertilizer integration in the past decades, covering a variety of fields such as technological innovation, application models, ecological effects, etc., and have achieved fruitful results, there are still obvious shortcomings in the current research in this field. On the one hand, the existing research results are scattered, lacking a systematic and comprehensive summary of the field of crop water–fertilizer integration, and it is difficult to form a complete knowledge system. On the other hand, with the explosive growth in the number of related research literature, the traditional method of reading and sorting literature in the face of massive data seems to be incompetent, and it is difficult to efficiently refine the key information and grasp the research vein. As a scientific research tool based on quantitative methods, bibliometric analysis can overcome the shortcomings of conventional review, systematically integrate past research results, objectively evaluate the current research status, and accurately predict the research hotspots and development trends through the statistics, analysis and visualization of literature data. At present, bibliometric methods have been widely used in various disciplines, showing unique advantages in revealing research patterns and assessing academic impact. However, in the field of crop water–fertilizer integration research, especially water–fertilizer coupling research on wheat, a globally important food crop, there is still a large gap in the international knowledge of its research status, hotspot distribution and development trend.

Wheat is a cornerstone of global food security, serving as the primary caloric and protein source for over 2.5 billion people (Snape et al., 2013). Its cultivation history can be traced back to the Neolithic era, and after thousands of years of varietal improvement and cultivation technology innovation, it has become an important cereal with wide adaptability and stable yield (Bell, 1987). According to the United Nations Food and Agriculture Organization (FAO) data in December 2024, the annual global wheat cultivation area was stable at more than 220 million hectares, and wheat production in 2024-2025 was estimated at 789 million tons, unchanged from the previous year (Zakharova and Zakharov, 2024). Wheat provides about 20% of dietary calories and proteins for human beings, and is not only a pillar of agricultural economy but also a matter of national food strategy security in the main producing regions of Asia, Europe and North America (Hegsted et al., 1954). In China, for example, wheat production in 2024 reached 140 million tons, a record high, accounting for a considerable proportion of the total global production (Sun et al., 2024); the United States Department of Agriculture (USDA) data show that the 2024-2025 U.S. wheat production is estimated to be 53.93 million tons, and the EU production is estimated to be 123 million tons (Guo et al., 2024).

Water–fertilizer coupling has become a core technology in improving wheat productivity and resource efficiency. By synchronizing water and nutrient delivery based on phenological requirements, this integrated management approach enhances photosynthesis, nutrient uptake, and physiological performance. Studies have shown that reasonable water–fertilizer coupling management can improve wheat water use efficiency by 25%-40% and fertilizer utilization by 15%-30%, while significantly reducing the risk of soil degradation and surface source pollution (Wang et al., 2024). This technical system relies on drip irrigation, sprinkler irrigation and other modern irrigation facilities, combined with soil testing and formula fertilizer application technology, to achieve the change from “experience irrigation” to “precision control”. For example, in the Yellow and Huaihai wheat areas of China, the integrated water–fertilizer model has increased wheat yields by 18%-22%and reduced nitrogen loss by 30% (Huang et al., 2024).

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As global climate change intensifies, the frequency of extreme precipitation events and seasonal droughts are highlighted, putting higher demands on wheat water and fertilizer management. During the 25-year period from 2000 to 2024, more than tens of thousands of research papers related to wheat water–fertilizer coupling have been published globally, covering a wide range of fields such as physiological response mechanisms, agronomic control technologies, and model simulations. However, these research results are scattered in different disciplines, and there are problems such as data fragmentation and duplication of conclusions. Based on this, this study systematically analyses the relevant literature in the field of water–fertilizer coupling research in wheat by using bibliometric methods with the help of tools such as VOS viewer, taking 2000-2024 as the time span. By sorting out the development history of the research in this field, the contributions of individuals, institutions and countries in the research process are assessed in depth; scientific data analysis methods are used to summarize the research hotspots; and combining the needs of agricultural development with the trend of technological development, the future research direction and development trend of wheat water–fertilizer coupling is pointed out prospectively, with the aim of providing new ideas for the subsequent research, and promoting the innovation and development of the water–fertilizer coupling technology in wheat. It is expected to provide new ideas for subsequent research, promote the innovation and application of wheat water–fertilizer coupling technology, and help achieve the goal of green, efficient and sustainable development of agriculture.

Materials and methods

Data sources and screening

Although a preliminary search indicated that there are tens of thousands of records related to wheat water–fertilizer research in the broader literature, this study strictly focused on the Web of Science Core Collection (WoS-CC) to ensure the high quality and academic rigor of the bibliometric analysis. The WoS-CC provides standardized citation data and complete metadata, which are essential for accurate knowledge mapping. By applying strict filtering criteria (e.g., excluding meeting abstracts, editorial materials, and non-English publications), we refined the dataset to 3193 high-quality articles and reviews. This screening process eliminates noise and ensures that the analysis reflects the most significant and peer-reviewed scientific contributions in the field.

The data retrieval process was conducted in three specific phases: (1) Database Selection: The Web of Science Core Collection was selected as the primary data source; (2) Search Strategy Formulation: A combination of keywords related to ‘wheat’, ‘water’, and ‘fertilizer’ was used to capture relevant literature (see specific search string below); and (3) Data Screening: The initial results were filtered by document type (Article and Review) and language (English), followed by the manual removal of irrelevant entries (e.g., duplicates or nonsense data). The detailed screening flow is illustrated in *Figure 1*.

Data visualization and analysis

This study adopts an integrated bibliometric and visualization approach to systematically analyze research trends, knowledge structure, and collaboration networks in the field of wheat water–fertilizer coupling from 2000 to 2024. Data analysis was conducted using VOSviewer (version 1.6.18), a specialized tool for bibliometric mapping

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and science visualization. In order to systematically analyze the research pattern and knowledge evolution in this field, the study integrated bibliometric methods and visualization techniques, and used VOS viewer (version 1.6.18) to construct the analysis framework.

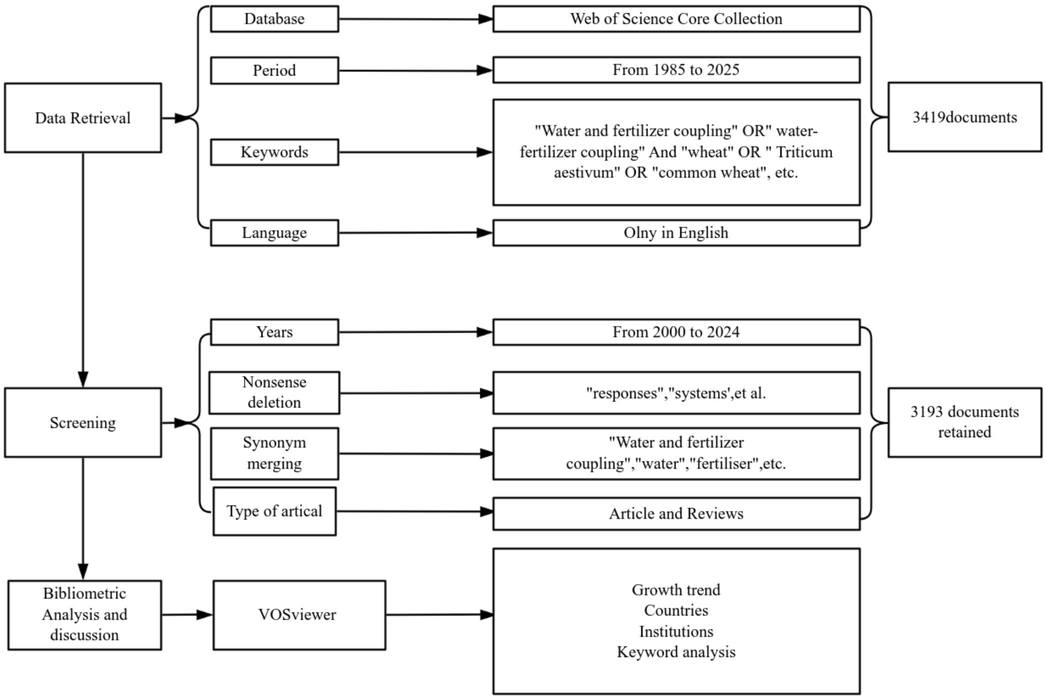

Figure 1. *The research flowchart of present study*

In the data pre-processing stage, basic index mining is carried out through VOS viewer: screening the top 20 countries, institutions and journals in terms of the number of publications to identify the core research power; extracting the top 30 high-impact literature in terms of the frequency of citations to reveal the key theoretical contributions in the field; and counting the top 20 high-frequency keywords in terms of the frequency of Keywords Plus to locate the hotspots of research. Meanwhile, based on VOS viewer, we construct inter-country co-authorship network, institutional coupling relationship, journal co-citation map and keyword co-occurrence network to visualize the knowledge structure in terms of cooperation network, academic influence and research themes. Systematically reveal the research characteristics and development trend in the field of wheat water–fertilizer coupling to provide a scientific basis.

Results

Publication trends

The annual number of publications in a field can indirectly assess the development of the field and the degree of attention it receives. By observing the changes in the annual number of publications in the field, it is possible to get an idea of the research trends and the level of activity in the field of study. The trend of citation frequency and publication distribution by year in the field of global wheat water–fertilizer coupling was plotted using the year as the horizontal coordinate and the vertical coordinate with publications measured on the left and cited literature on the right (*Fig. 2*).

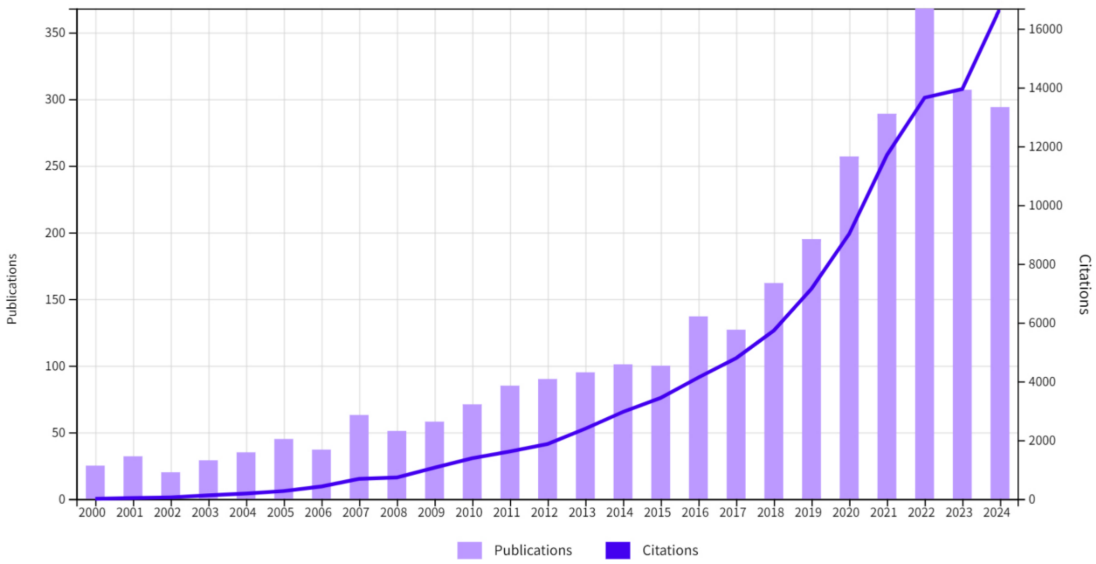

***Figure 2.** Trends in the global distribution of citations and publications by year in the field of water–fertilizer coupling in wheat*

In recent years, the number of publications in the field of wheat water–fertilizer coupling by scholars around the world has generally shown an upward trend, but also fluctuated to some extent in individual years. In the WOS database, the number of publications was not less than 20 per year, among which, the number of publications in the field was low in 2000-2015, all of which were less than 100, and then began to show an upward trend, reaching a maximum of 368 publications in 2022, of which the citation frequency was as high as 13,638. while the lowest number of publications was in 2002, which was only 20, of which the citation frequency was as low as 54; the number of publications in the field of the overall upward trend in the number of articles shows that the research in this field is increasing. Combined with the global trend of the number of publications, it can be concluded that the research on water–fertilizer coupling in wheat is still a hot topic for the present and future research.

National and institutional distribution of literature

Figure 3 presents the distribution of publications and collaborative networks of 113 countries in the field of wheat water–fertilizer coupling research based on literature data from 2000 to 2024. The study shows that China ranks first with 1172 publications, and its node size is significantly prominent in the knowledge graph, which confirms China’s central position in this field of research. China has established cooperative relationships with 56 countries, with the highest intensity of cooperation with the United States, followed by cooperation with India, and this cooperative network mainly focuses on the research and development and application of water and fertilizer management technologies in arid and semi-arid regions.

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The U.S. ranks second with 532 publications, but its cooperative network covers 82 countries, demonstrating a broader international collaboration capability. Network density analysis reveals that the total link strength of the U.S.-led collaborative network is 698, and that of the U.S.-led collaborative network is 482, with the two countries forming an advantage in cross-regional technology integration and multi-scale model construction. In contrast, China takes the lead in terms of the number of articles published and the total link strength of the collaborative network, reflecting that there is still room for improvement in the depth and breadth of collaboration.

The results show that the global wheat water–fertilizer coupling research has formed a bipolar cooperation pattern with China and the United States as the core, but China still needs to strengthen the radiation scope of international cooperation and the efficiency of resource integration. In the future, we can deepen the international cooperation and promote the global adaptive transformation of the research results through the establishment of a regular international joint research mechanism, the sharing of field trial database, and the collaborative development of intelligent water and fertilizer management system, so as to enhance China's international discourse and technological leadership in this field.

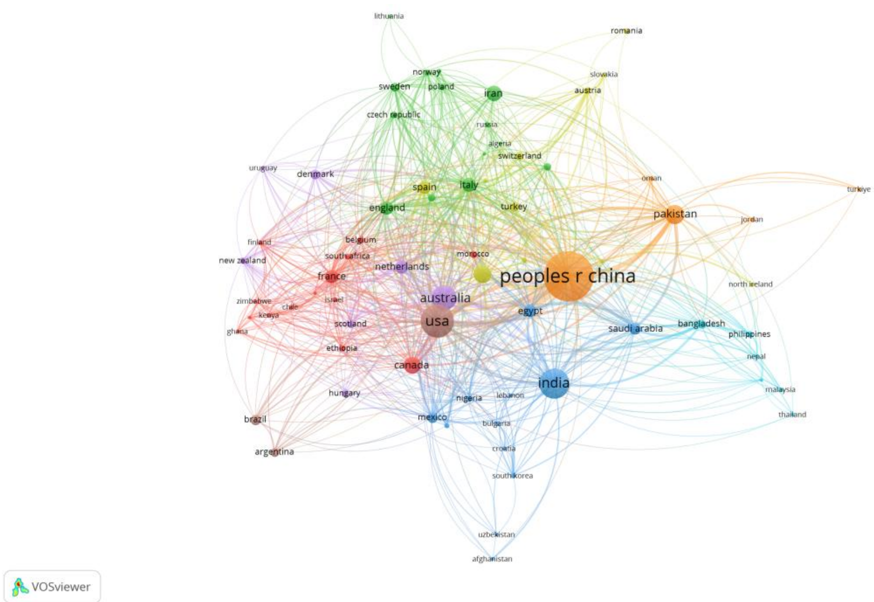

Figure 3. *Network map of countries and their partnerships in the field of water–fertilizer coupling in wheat*

The analysis of institutional cooperation can clearly present the contribution of each organization in the field of wheat water–fertilizer coupling research and the interaction between institutions. *Figure 4* shows the results of the institutional literature coupling analysis with the help of the Scientific Knowledge Graph: the Chinese Academy of Sciences (CAS), as the core node of the field, tops the list with 255 articles, has the largest total link strength and the most extensive association with other institutions; the Chinese Agricultural University (CAU) and Northwest Agriculture and Forestry University (NWAFU), which have published 191 and 170 articles, respectively, have also played a key role in the academic cooperation network. The results of this analysis echo the

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research trends based on the country dimension in *Figure 3,* further demonstrating China’s significant advantages and leading position in the field of water–fertilizer coupling research in wheat globally.

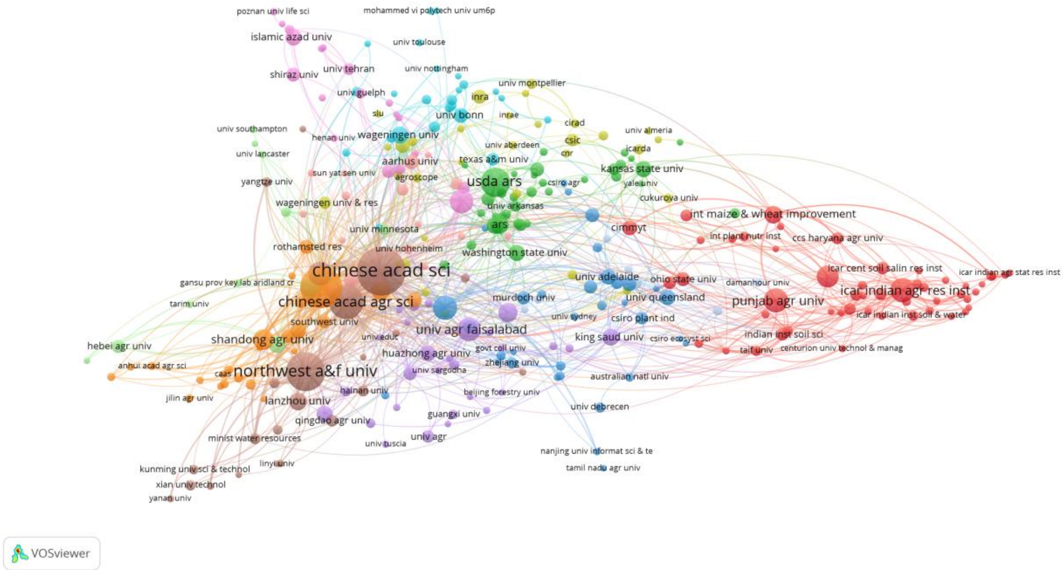

Figure 4. *Map of institutional co-operation in the field of water–fertilizer coupling research in wheat*

Main journals and authors

In this study, a systematic study of source journals using co-citation analysis was conducted with the aim of accurately identifying the core journals and knowledge base in the field of water–fertilizer coupling research in wheat. *Figure 5* illustrates the co-citation knowledge map containing 184 journals, which reveals the scientific association network among journals in depth through visualization.

It was found that *Field Crops Research* was the most cited journal in the field with 10,065 citations, and it presented the largest node in the knowledge graph, indicating that it has a very high impact in the field; *Agricultural Water Management* ranked second with 7698 citations, and *Agriculture Ecosystems & Environment* followed with 4242 citations. Of particular interest is the strongest line between *Field Crops Research* and *Agricultural Water Management*, a quantitative feature that intuitively indicates a high degree of co-occurrence in academic citations between the two journals, suggesting that there is a strong intrinsic connection between the two journals in terms of research topics and academic values. The above three journals, especially Field Crops Research, constitute an important academic cornerstone in the field of water–fertilizer coupling in wheat by virtue of their significant citation frequency.

Based on the cluster analysis, the knowledge graph can be clearly deconstructed into four distinctive journal clusters: the orange cluster, with *Field Crops Research* as the core, focuses on the optimization of wheat water and fertilizer management strategies and the research and development of green production technologies; the blue cluster, with *Agricultural Water Management* as the hub, focuses on exploring the path of sustainable development in the whole life cycle of wheat production; the purple cluster, with Agronomy-Basel as the center, carries out in-depth research on soil fertility optimization

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and monitoring technology innovation and optimization of planting practices; and the purple cluster, with European The purple cluster, centered on *Agronomy-Basel*, focuses on the optimization of soil fertility, technological innovations in monitoring and optimization of planting practices; and the flesh-colored cluster, headed by *European Journal of Agronomy*, is dedicated to exploring the precise allocation of water and fertilizer resources in order to achieve synergistic improvement of wheat yield and quality. The research results show that the academic results in the field of wheat water–fertilizer coupling are mainly published in professional journals such as Plant Science, Environmental Science, Soil Science, Crop Science and other comprehensive agricultural science journals, which together constitute an important platform for academic exchange and knowledge dissemination in this field.

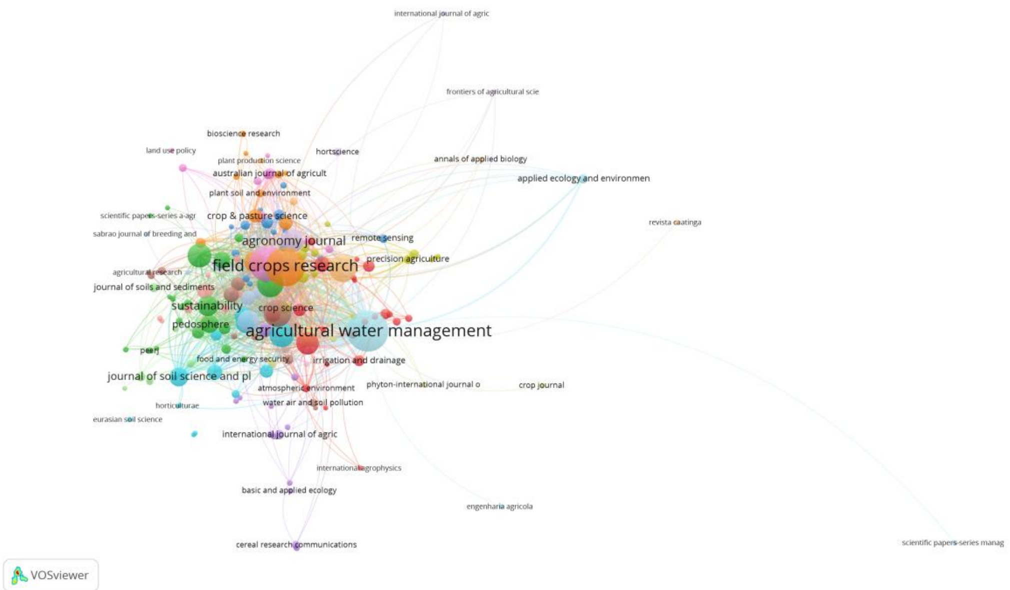

Figure 5. *Journal co-citation knowledge graph*

Figure 6 shows the author cooperation network diagram using node visualization to present the collaborative relationship of the research group, the node size strictly corresponds to the total contact strength, and only the close contact with a frequency higher than 3 times (accounting for the top 20%) is shown by setting a threshold. From the figure, it can be clearly observed that the academic cooperation shows a star-like radiation pattern with core authors as the hub: Zhang fucang and Fan junliang from Northwest Agriculture and Forestry University have formed a stable interdisciplinary research cluster by relying on the strengths of the research on dryland agriculture in China; Kadambot, H. M. and Lal, Ral, both from Sultan Qaboos University, have formed a stable interdisciplinary research cluster by relying on the strengths of the research on dryland agriculture in China. Kadambot, H. M. Siddique and Lal, Rattan from Sultan Qaboos University have launched a collaborative research on special agro-ecosystems in the Gulf region; Jat, M. L. and Datta, Ashim from the International Crops Research Institute for the Semi-Arid-Tropics (ICRISAT) are focusing on semi-arid agriculture, and their team is focusing on semi-arid agriculture. Ashim of the International Crops Research Institute for the Semi-Arid-Tropics (ICRISAT), and an international collaborative network focusing on crop improvement in semi-arid regions.

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Quantitative analysis of the TLS (Total Link Strength) values in the VOS viewer shows that the team of Prof. Zhang Fucang (TLS = 102), the team of Associate Prof. Fan Jungliang (TLS = 85) and the team of Researcher Guo Jinjin (TLS = 77) from Northwest Agriculture and Forestry University (NWAFU) ranked in the top three among all the collaborating clusters, which is on average 43% higher than that of the next tier of teams. This data not only reflects that Chinese scholars have become more active in the field of crop water–fertilizer coupling, but also reflects that domestic research institutions have formed a research echelon with international influence in this field. However, there are still significant geographical and academic barriers, and most teams are still in a relatively closed research status.

The reasons for this are the increased cost of communication due to geographic isolation (e.g. the average physical distance between ICRISAT and domestic institutions is more than 8000 km), conflicting research paradigms due to differences in academic systems, and the lack of cross-institutional co-funding mechanisms, all of which constrain the expansion of collaborative networks. In view of this situation, it is suggested that the sharing of academic resources and in-depth cooperation among different institutions can be promoted through the establishment of international academic alliances, joint research funds and digital collaboration platforms, so as to promote the transformation of the research on crop water–fertilizer coupling from decentralized exploration to collaborative innovation mode.

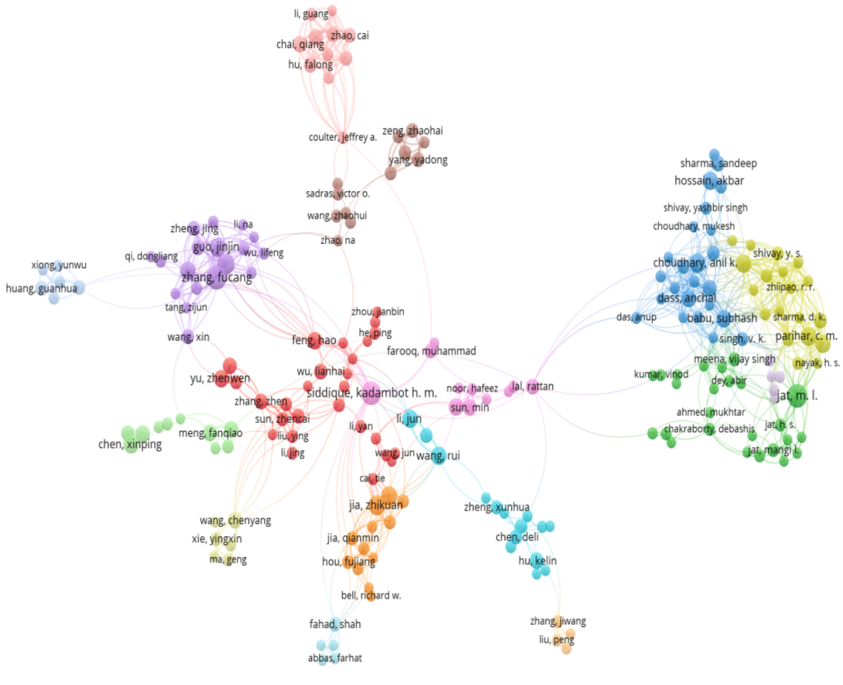

Figure 6. *Author's collaborative web chart*

Most influential papers

A total of 13,395 authors contributed to 3193 articles on wheat water–fertilizer coupling in this dataset. The top 30 cited articles were selected for a focused bibliometric analysis to determine their impact on the development of wheat water–fertilizer coupling research. One of the journal citation metrics is a measure of the average discipline-normalized citation impact (CNCI) of citable items (literature and reviews) published by

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journals in the last three years, which gives a visual indication of the academic level of scholars researching in the field of wheat water fertilization coupling. The most cited article was published by Lal, Rattan etc. in 2004 in *Science*, with 5143 citations, a journal impact factor of 44.8, and a journal citation index of 9.9. The next most highly cited articles were published by Ju, XT, Xing, GX etc. in 2009 in *Proceedings of the National Academy of Sciences of the United States of America* by Ju, XT, Xing, GX etc. in 2009 and *Nature* by Mueller, ND, Gerber, JS etc. in 2012. These articles are highly recognized in the field for their number of citations. The analyses show that research on water–fertilizer coupling in millet mainly involves collaboration between international institutions, which highlights the need for greater international cooperation.

According to the content of these 30 papers (*Table A1*), the research in the field of wheat water–fertilizer coupling includes: (1) morphological studies on wheat root morphology, root-shoot ratio, leaf stomatal characteristics and stem mechanical strength under different water–fertilizer combination conditions; (2) studies revealing wheat's adaptation mechanism to water–fertilizer coupling by exploring changes in photosynthetic characteristics, accumulation of osmotic adjustment substances (such as proline and soluble sugars), hormone (such as abscisic acid and auxin) balance and antioxidant enzyme system activity and other physiological and biochemical indexes; (3) research on mining and identifying functional genes related to efficient water–fertilizer utilization in wheat and on the growth performance and physiological responses of transgenic wheat under water–fertilizer coupling conditions; (4) genetic diversity analysis of wheat varieties using molecular marker technologies (such as SSR and SNP) and molecular breeding and variety selection of wheat based on water–fertilizer coupling requirements; (5) comprehensive application of cultivation technologies in water–fertilizer coupling such as precision irrigation systems (irrigation amount, irrigation time, irrigation frequency, etc.), reasonable fertilization strategies (fertilizer type, fertilization amount, fertilization period, etc.), planting density optimization and seed pretreatment (seed soaking, seed coating, etc.). In general, it mainly involves morphological, physiological and biochemical, molecular response mechanism research and breeding and cultivation technology research for efficient water–fertilizer utilization.

Analysis of research hot spots and trends

The detailed list of the top 30 most cited papers is provided in *Table A1* in the *Appendix*.

Keyword co-occurrence analysis

Through the keyword co-occurrence analysis, the results of WOS core database literature network are shown in *Figure 7* and *Table 1*. each node represents a keyword respectively, the size of the node chronology inverse the frequency of keyword occurrence, the yellow circle on the node chronology represents high centrality, and the green circle represents high emergence. According to the keyword co-occurrence mapping, the top 30 high-frequency keywords were extracted (*Table 1*), and the top 3 terms in terms of their keyword frequency in the literature were wheat, yield, and management. The total link strength (TLSf) represents the centrality of the keywords, in which the terms "water use efficiency" and "use efficiency" have high centrality, which further indicates that scholars in the field of water–fertilizer coupling in wheat are mostly focusing on the research of these technologies, and these terms promote the transmission and integration of information between different branches of research, guiding the

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focusing of scientific research efforts and the development of a new technology. It is of great significance to promote the innovation of agricultural wheat water coupling technology and the sustainable development of agriculture.

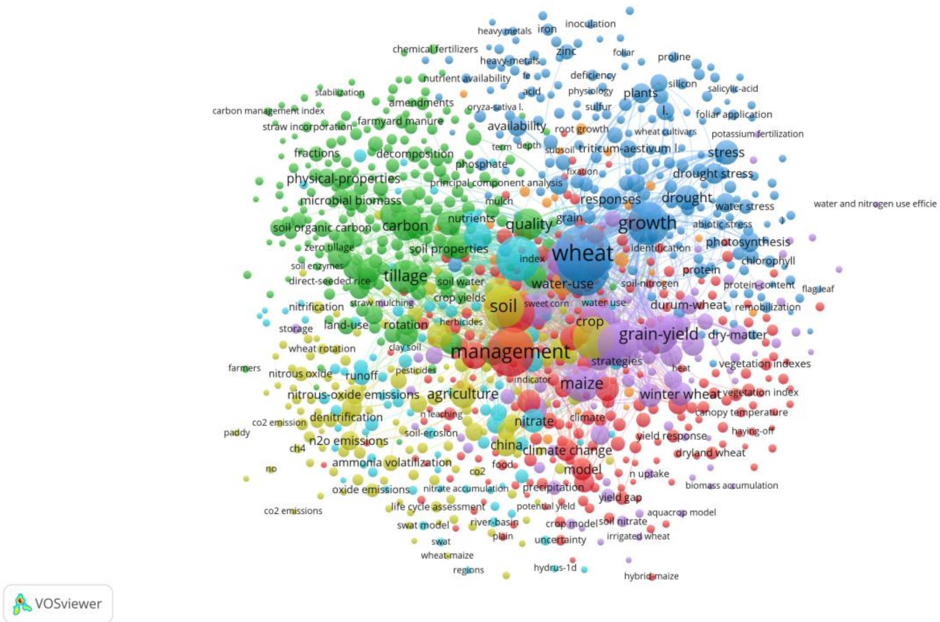

Figure 7. *Keyword co-occurrence analysis chart*

Table 1. *Top 20 high-frequency keywords*

Rank	Keyword plus	Cluster	Occurrences	Links	TLS[f]
1	Wheat	3	637	916	8113
2	Yield	3	719	878	6395
3	Management	1	637	867	5836
4	Nitrogen	6	535	827	4812
5	Winter-wheat	5	483	760	4331
6	Growth	3	468	732	4071
7	Irrigation	4	438	728	4023
8	Use efficiency	5	397	716	3738
9	Soil	4	421	738	3668
10	Grain-yield	5	345	644	3326
11	Water	1	374	725	3264
12	Fertilization	5	353	680	3181
13	Maize	5	307	636	2904
14	Water-use efficiency	5	280	612	2582
15	Tillage	2	265	578	2436
16	Productivity	5	256	611	2398
17	Quality	2	220	575	1963
18	Fertilizer	4	207	546	1939
19	Carbon	2	174	489	1575
20	Rice	4	167	506	1543

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Discussion

Climate change, food insecurity, water scarcity, and population growth are among the most pressing global challenges today (Hanjra and Qureshi, 2010). As a core bottleneck of agricultural production, water and fertilizer coupling imbalance has become a key factor restricting global wheat yield improvement. With the intensification of global warming, the contradiction between spatial and temporal matching of water and nutrients in agricultural fields is becoming more and more prominent, and its complexity and impact scope are expected to continue to expand (Costa et al., 2022). In the past three decades, the effects of water–fertilizer coupling on wheat growth and development, yield formation and quality regulation have become a research focus in the field of agroecology, and an important scientific issue for ensuring global food security. Therefore, it is of urgent practical significance to systematically sort out the research status and cutting-edge trends of the interaction mechanism between water–fertilizer coupling and wheat in order to enhance the efficiency of resource use and stable yield of wheat. Through bibliometric analysis and knowledge mapping, this study reveals that the current research on water–fertilizer coupling in wheat focuses on two main directions: the analysis of crop response mechanism to water–fertilizer coupling, and the innovation of efficient cultivation technology based on synergistic regulation.

Water–fertilizer coupling mechanisms

Morphological, physiological and biochemical response mechanisms under coupled water–fertilizer conditions

Under coupled water–fertilizer conditions, wheat exhibits notable morphological adaptations, particularly in its leaf and root systems, to optimize growth and development (Wang et al., 2024b). Leaf, as the main interface with the external environment, is highly sensitive to changes in water and fertilizer conditions (Kannan, 2010). Water–fertilizer coupling affects leaf morphology in wheat, which in turn alters leaf area ratio (LAR), specific leaf area (SLA) and leaf weight ratio (LWR) (Wang et al., 2024c). For example, when water is abundant and nutrients are in good supply, SLA and LAR increase because plants increase photosynthetic efficiency by increasing leaf area to promote growth (Amanullah et al., 2007), whereas when water and nutrients are in relatively low supply, SLA and LAR decrease, and plants reduce water transpiration losses by decreasing leaf area while prioritizing the allocation of resources to the root system to increase nutrient uptake capacity (Freschet et al., 2015). These morphological changes can be used to screen wheat varieties for different water and fertilizer conditions.

The root system, as a critical component of the soil–plant–atmosphere continuum, plays a vital role in determining wheat's efficiency in water and nutrient uptake (Mălinaș et al., 2022). Under water–fertilizer coupling conditions, the volume and length of the wheat root system will change accordingly (Wang et al., 2024b). For example, when water is sufficient and nutrients are abundant, the root system will grow moderately to absorb excess nutrients (Nambiar, 1990); while when water and nutrient supplies are insufficient, the root system will preferentially grow into the deep soil, increase root length and root volume, and expand the root-soil contact area, thus enhancing the plant's ability to absorb water and nutrients from the deep soil (Schenk and Jackson, 2002). This adaptive change in the root system helps wheat to maintain good growth under different water and fertilizer conditions (Calleja-Cabrera et al., 2020).

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It has been shown that under appropriate water–fertilizer coupling conditions, larger leaves and robust root system of wheat help to accumulate higher biomass yield (Curtis and Halford, 2014). In addition, the root-crown ratio of wheat is particularly sensitive to water–fertilizer coupling conditions, and its changes reflect the balance of water and nutrient uptake and utilization by the plant, which is an important morphological indicator for assessing the efficiency of water and fertilizer use in wheat. Changes in root-crown ratio can reflect the growth strategy of wheat under different water–fertilization conditions (van der Bom et al., 2024), for example, when water–fertilization is sufficient, the root-crown ratio is relatively low, indicating that the plant allocates more resources to the above-ground part to promote growth; whereas when water–fertilization is insufficient, the root-crown ratio increases, indicating that the plant allocates more resources to the root system to enhance the uptake capacity of water and nutrients (Sainju et al., 2017).

To optimize water and fertilizer use efficiency, wheat employs a range of physiological and biochemical strategies, and these responses can be grouped into five main areas.

(1) Water metabolism and nutrient uptake: Leaf water potential and relative water content (RWC) of wheat are significantly affected under water–fertilizer coupling conditions (Dehkordi, 2016). When water supply is sufficient, leaf water potential is higher and RWC is larger (Matin et al., 1989), while when water supply is insufficient, leaf water potential decreases and RWC decreases (Brown et al., 1976). Meanwhile, nutrient supply also affects water use efficiency (WUE) and nutrient use efficiency (NUE) of wheat (Salim and Raza, 2020). For example, nitrogen is one of the key nutrients for plant growth, and an adequate supply of nitrogen can improve the efficiency of photosynthesis, thus promoting water use (Fathi, 2022); whereas phosphorus is closely related to energy metabolism, and an adequate supply of phosphorus can improve the efficiency of water uptake and utilization by plants (Veneklaas et al., 2012). In addition, leaf surface cuticle waxes play a key role in improving plant water use efficiency under water–fertilizer coupling conditions by reducing cuticle water loss (Lopez-Zaplana et al., 2020). It has been investigated that wax content is more sensitive to water–fertilizer coupling conditions than total wax content, and the increase in alkane content is particularly significant in improving water–fertilizer use efficiency, which can be used as a potential indicator for screening wheat varieties suitable for water–fertilizer coupling conditions (Feng et al., 2020). Meanwhile, the type and amount of wheat root secretions can also be changed by water–fertilizer coupling conditions, and these secretions can influence the structure of soil microbial communities, which in turn affects nutrient conversion and uptake efficiency (Gan et al., 2023).

(2) Photosynthesis and nutrient use: water–fertilizer coupling conditions affect chlorophyll biosynthesis and catabolism, and consequently photosynthetic efficiency (Liang et al., 2024). Studies have shown that under water–fertilizer coupling conditions, chlorophyll a and b as well as photochemical efficiency of wheat change depending on the balance of water and fertilizer supply (Ramesh et al., 2017). When water and nutrient supply are sufficient, chlorophyll content is higher and photosynthetic efficiency is higher, while when water and fertilizer supply are insufficient, chlorophyll content decreases and photosynthetic efficiency decreases (Waraich et al., 2011). In addition, nutrient supply also has important effects on the activity of photosynthesis-related enzymes and the synthesis and transport of photosynthetic products (Lu et al., 2025). For example, nitrogen is an important component of chlorophyll and photosynthesis-related enzymes, and adequate nitrogen supply can improve photosynthetic efficiency (Qiang et

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al., 2023); phosphorus is involved in the transport of photosynthesis products and energy metabolism, and adequate supply of phosphorus can promote the distribution and utilization of photosynthesis products (Rychter and Rao, 2005). Therefore, the response of wheat photosynthesis under water–fertilizer coupling conditions is the result of the joint action of water and nutrient supply.

(3) Compatible solutes and osmoregulation: under water–fertilizer coupling conditions, wheat accumulates organic osmoregulators such as proline, betaine, soluble proteins (SP) and soluble sugars (SS), which increase with water–fertilizer coupling conditions (Halford, 2011). Studies have shown that wheat varieties adapted to water–fertilizer coupling conditions accumulate more osmoregulatory substances than non-adapted varieties. These osmoregulatory substances not only regulate intracellular osmotic pressure and maintain cell expansion and structural stability, but also act as signaling molecules involved in plant response and adaptation processes to water–fertilizer conditions (Chen and Jiang, 2010). For example, the accumulation of proline can regulate the intracellular redox state and protect the cells from damage; the increase of soluble sugars can provide energy and carbon sources and maintain the metabolic activities of the cells (Alagoz et al., 2023).

(4) Antioxidant defense: The adaptation of wheat to water–fertilizer coupling conditions is closely related to its antioxidant capacity (Kumar et al., 2022). Under water–fertilizer coupling conditions, the activities of antioxidant enzymes (e.g., superoxide dismutase SOD, peroxidase POD, and catalase CAT) are significantly enhanced, which helps plants to enhance the efficiency of water and fertilizer use (Wang et al., 2022). Varieties with stronger antioxidant responses typically exhibit lower membrane damage, as indicated by reduced malondialdehyde (MDA) levels and electrolyte leakage. Additionally, non-enzymatic antioxidants like glutathione and flavonoids play key roles in ROS scavenging under stress conditions (Shuang et al., 2023).

(5) Endogenous and exogenous hormones orchestrate wheat's responses to water–fertilizer coupling. Abscisic acid (ABA) is particularly important in regulating stomatal closure and promoting root growth under water-deficit conditions (Lin, 2024). For example, growth hormone regulates the direction and morphology of root growth and promotes root growth towards water and nutrient-rich areas; gibberellin regulates cell elongation and division and affects plant height and grain number of spikes in wheat; and ethylene regulates stomatal closure and root development and enhances the adaptive capacity of plants. Overall, these physiological and biochemical responses collectively enhance the adaptive capacity of wheat under coupled water–fertilizer conditions, highlighting the complexity and adaptability of this crop in optimizing water and fertilizer use efficiency.

Molecular response of water–fertilizer coupling mechanisms

With the rapid advancement of molecular biology technologies, research on water–fertilizer coupling in wheat has extended from physiological and morphological levels to the molecular scale. Key research areas include the identification of functional genes, and systematic investigations using transcriptomics, metabolomics, and proteomics. Transcription factors, in particular, have emerged as pivotal regulators in wheat's adaptive response to coupled water and nutrient supply.

For example, MicroRNA156 (miR156) regulates the squamous promoter binding protein (SPL) gene family, which acts as a transcription factor and subsequently regulates the expression of downstream genes, thereby modulating the growth and developmental

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network of wheat (Jerome Jeyakumar et al., 2020). It has been shown that miR156 influences the response of wheat to water and fertilizer conditions by regulating the expression of the SPL gene family in wheat. Wheat genotypes overexpressing miR156 (referred to as miR156OE) showed significantly higher tolerance under water–fertilizer coupled conditions compared to wild-type controls (WT). miR156OE genotypes not only showed superior performance in water use efficiency (WUE) and nutrient use efficiency (NUE), but also maintained higher photosynthetic efficiency, compatible solute (e.g., proline) accumulation, and antioxidant levels (Wang and Wang, 2015). Likewise, downregulation of SPL13, a target of miR156, results in improved photosynthetic efficiency, enhanced nutrient uptake, and elevated WUE, indicating that miR156 contributes to improved water–fertilizer coupling performance via repression of SPL13 (Ren et al., 2022).

Transcriptomic analyses reveal gene expression patterns across wheat genotypes, tissues, and developmental stages under diverse water and nutrient regimes, enabling the identification of candidate genes and regulatory networks. For example, sensitivity to abscisic acid (ABA) during seed germination is heritable in wheat, and screening for ABA-responsive genotypes may aid in selecting lines with superior adaptability to water–fertilizer coupling conditions (Morgan, 1980).

Metabolomics studies aim to identify specific traits associated with water and fertilizer use efficiency by examining the molecular phenotypes of wheat under water–fertilizer coupled conditions (Van Hintum and Brink, 2019). It was shown that moderate levels of miR156 overexpression led to suppression of SPL13 and increase in WD40-1, which fine-tuned DFR expression to enhance anthocyanin biosynthesis, which together with the accumulation of other stress-relieving metabolites and physiological responses, contributed to water–fertilizer coupling efficiency (Arshad and Hannoufa, 2022). The major classes of differential metabolites include amino acids, organic acids, sugars and alkaloids such as salicylic acid (SA), indole-3-acetic acid (IAA), gibberellin A4 (GA4), abscisic acid (ABA), sucrose, L - phenylalanine, L - tyrosine, succinic acid, and nicotinic acid, which are required for water–fertilizer-coupling capacity in wheat (Lv et al., 2021).

Proteomics studies are increasingly reporting the response of wheat to water–fertilizer-coupled conditions. Water–fertilizer-coupled response proteins are involved in a variety of cellular functions in the wheat root system, which include energy metabolism, signaling pathways, antioxidant mechanisms, stress defense mechanisms, transcriptional and translational processes, reactive oxygen species (ROS) regulation, abscisic acid (ABA) biosynthesis, calcium signaling and storage processes. For example, the protein expression profiles in wheat roots changed significantly under different water and fertilization conditions, and a variety of differentially abundant proteins (DAPs) were identified, which were mainly involved in defense responses, energy metabolism, protein synthesis and degradation, oxidative stress and carbohydrate metabolism. The changes of these proteins were closely related to the water–fertilizer coupling ability of wheat, providing an important molecular basis for optimizing the water–fertilizer use efficiency of wheat (Cheng et al., 2015). These studies not only reveal the molecular basis of wheat adaptation to water–fertilizer coupling conditions, but also provide a theoretical basis for the breeding of wheat varieties that use water and nutrients efficiently.

Optimization of water and fertilizer coupling in breeding and cultivation of wheat

Efficient water–fertilizer coupling is a vital strategy for improving wheat yield, resource use efficiency, and agro-ecological sustainability. As global agriculture faces

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increasing pressure from resource constraints and environmental challenges, the breeding of resource-efficient cultivars and the refinement of cultivation techniques have become essential components of sustainable wheat production.

Optimized water–fertilizer coupled breeding technology

Currently, conventional techniques such as selection breeding and crossbreeding still play an important role in wheat breeding, while molecular techniques are gradually being integrated into wheat breeding strategies. There are various selection breeding methods, including monoculture selection and hybrid selection. For example, through single-plant selection of wheat under specific environmental conditions, it is possible to select superior varieties that are adapted to specific water and fertilization conditions. Hybrid breeding, on the other hand, produces progeny with superior traits through crosses between individuals of different genotypes (Kiszonas et al., 2018). For example, some high-yielding wheat varieties have been developed through crossbreeding between different varieties, which show higher yields and better adaptation under specific water and fertilization conditions.

Molecular breeding technologies, particularly marker-assisted selection (MAS), enable the precise identification of genes and quantitative trait loci (QTLs) associated with WUE and NUE. This facilitates rapid screening and selection of elite genotypes, thereby accelerating the breeding cycle (Feng et al., 2019). For example, varieties with efficient water use efficiency (WUE) and nutrient use efficiency (NUE) can be rapidly identified through molecular marker-assisted selection, shortening the breeding cycle (Javed et al., 2022). In addition, gene editing technology provides more precise tools for wheat breeding. For example, modification of key genes in wheat by gene editing technology can enhance its adaptability to water and fertilization conditions.

Transgenic technology also offers new possibilities for optimizing water–fertilizer coupling in wheat. For example, by introducing exogenous genes related to water use efficiency or nutrient uptake, the growth performance of wheat under different water and fertilizer conditions can be improved (Hafeez et al., 2024). It has been shown that the introduction of certain genes can enhance the tolerance of wheat to drought and nutrient deficiencies, thereby improving its yield and quality under water–fertilizer coupling conditions.

Optimized water–fertilizer coupling cultivation techniques

Cultivation strategies play a pivotal role in enhancing water–fertilizer coupling efficiency in wheat production. Among these, precision irrigation and fertilization technologies are central to improving resource use efficiency. The application of water–saving irrigation systems, such as drip and sprinkler irrigation, when combined with site-specific nutrient management, allows for the precise delivery of water and fertilizers according to the physiological needs of the crop and real-time soil conditions (Lakhiar et al., 2024). In addition, reasonable adjustment of the time and amount of irrigation and fertilizer application can further improve the efficiency of water–fertilizer coupling.

The application of organic and bio-fertilizers is also an important measure to optimize water–fertilizer coupling. Organic fertilizers can improve soil structure and increase soil water retention and nutrient supply capacity. For example, the application of compost or green manure can increase the soil organic matter content, thus enhancing the water retention and nutrient supply capacity of the soil (N'Dayegamiye and Tran, 2001).

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Biofertilizers such as rhizobacteria can promote nutrient uptake in wheat and improve nutrient use efficiency (Shaharoona et al., 2008).

The application of plant growth regulators can also improve the adaptability of wheat to water and fertilizer conditions. For example, growth regulators can promote the growth of wheat root system and enhance its ability to absorb water and nutrients (Rajala et al., 2001). In addition, the use of beneficial microbial strains such as mycorrhizal fungi can improve the root environment of wheat and enhance its water and fertilizer uptake efficiency.

A rational wheat cropping pattern is also an important aspect of optimizing water–fertilizer coupling. Wheat can be grown as a monocrop or in a crop rotation or intercropping system. For example, rotation of wheat with legumes can improve soil fertility and water and fertilizer use efficiency. A rational cropping pattern needs to take into account the interactions between wheat and other crops to achieve optimal water–fertilizer coupling.

In addition, optimizing nutrient management, weed control and pest management during cultivation is also key to achieving optimal water–fertilizer coupling. Tailored fertilization programs ensure nutrient supply aligns with developmental stages; effective weed suppression reduces competition for nutrients; and timely pest and disease interventions minimize stress, all of which support enhanced physiological responses to coupled water–nutrient inputs (Singh and Singh, 2021).

Conclusion

This study conducted a comprehensive bibliometric analysis of 3193 articles related to “wheat” and “water–fertilizer coupling” retrieved from the Web of Science Core Collection. The results of this study show that the research in the field of water–fertilizer coupling in wheat has shown a steady growth in recent years, and the related research results have been emerging continuously. From the perspective of countries, China has made the most outstanding contribution to the research in this field, with a total of 1172 articles published, occupying an important position; the United States followed with 532 articles. Among the many academic journals, Field Crops Research is particularly outstanding, with 10,065 citations, which fully demonstrates the authority and influence of the journal in the field of water–fertilizer coupling research in wheat.

Through in-depth analyses of the top 30 cited literature and high-frequency keywords, the present study accurately grasps the key development of the field of water–fertilizer coupling in wheat. Currently, the research focuses on investigating the response mechanisms of wheat under water–fertilizer deficit conditions, covering morphological, physiological, biochemical and molecular responses. At the same time, with the increasing concern about drought, research on water–fertilizer coupled breeding technology and optimized cultivation technology has also received more and more attention, which has become a key driving force for the development of the field.

Looking ahead, the study of physiological, biochemical and molecular response mechanisms in wheat will remain a core research direction and is expected to continue to make breakthroughs. In addition, transgenic wheat technology as well as innovative research in the field of nutrient management, such as the application of microbial fertilizers, will become hotspots and focuses of future research, and their importance is likely to be further highlighted to provide new ideas and methods to solve the water and fertilizer use efficiency problems in wheat production.

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The main objective of this study is to provide solid theoretical support for the research on water–fertilizer coupling in wheat and to help researchers better grasp the research dynamics and development trends in this field, so as to contribute to the improvement of wheat crop yields, food security and the promotion of sustainable agricultural development.

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APPENDIX

Table A1. *The 30 most cited papers on water–fertilizer coupling in wheat*

Rank	Title	Journal	Year	JC	JIF	JCI
(1)	Soil carbon sequestration impacts on global climate change and food security	Science	2004	5190	44.8	9.9
(2)	Reducing environmental risk by improving N management in intensive Chinese agricultural systems	Proceedings of the National Academy of Sciences of the United States of America	2009	2157	9.4	2.4
(3)	Closing yield gaps through nutrient and water management	Nature	2012	2008	50.5	11.3

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(4)	The Millennium Drought in southeast Australia (2001-2009): Natural and human causes and implications for water resources, ecosystems, economy, and society	Water Resources Research	2013	1015	4.6	1.22
(5)	Constraints and potentials of future irrigation water availability on agricultural production under climate change	Proceedings of the National Academy of Sciences of the United States of America	2014	772	9.4	2.4
(6)	Drought and salinity: a comparison of their effects on mineral nutrition of plants	Journal of Plant Nutrition and Soil Science	2005	763	2.6	0.71
(7)	Evaluating cover crops for benefits, costs and performance within cropping system niches	Agronomy journal	2005	728	2	0.73
(8)	A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: effects of water regime, crop residue, and fertilizer application - art. no. GB2021	Global Biogeochemical Cycles	2005	666	5.4	1.2
(9)	Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize	Agricultural Water Management	2004	649	5.9	1.89
(10)	Applications of remote sensing in precision agriculture: a review	Remote Sensing	2020	613	4.2	0.97
(11)	Productivity and management of rice-wheat cropping systems: issues and challenges	Field Crops Research	2001	592	5.6	1.91
(12)	Direct seeding of rice: recent developments and future research needs	Advances in Agronomy	2011	578	9.265	1.12
(13)	Microbial phytase in poultry nutrition	Animal Feed Science and Technology	2007	556	2.5	1.23
(14)	Improving crop productivity and resource use efficiency to ensure food security and environmental quality in China	Journal of Experimental Botany	2012	484	5.8	1.41
(15)	Crop Residue Removal Impacts on Soil Productivity and Environmental Quality	Critical Reviews in Plant Sciences	2009	465	6	0.7
(16)	Internet of Things (IoT) and Agricultural Unmanned Aerial Vehicles (UAVs) in smart farming: a comprehensive review	Internet of Things	2022	428	6	1.32
(17)	Responses of Wheat Yield, Macro- and Micro-Nutrients, and Heavy Metals in Soil and Wheat following the Application of Manure Compost on the North China Plain	Plos One	2016	428	2.9	0.88
(18)	A Review of Methods for Sensing the Nitrogen Status in Plants: advantages, Disadvantages and Recent Advances	Sensors	2013	425	3.4	0.87

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(19)	Plant nutrition research: priorities to meet human needs for food in sustainable ways	Plant and Soil	2002	420	3.9	1.17
(20)	Managing soils to achieve greater water use efficiency: a review	Agronomy Journal	2001	413	2	0.73
(21)	Fertilizers and nitrate pollution of surface and ground water: an increasingly pervasive global problem	SN Applied Sciences	2021	388	2.8	0.46
(22)	Soil management in relation to sustainable agriculture and ecosystem services	Food Policy	2011	348	6.8	1.83
(23)	Low-altitude, high-resolution aerial imaging systems for row and field crop phenotyping: a review	European Journal of Agronomy	2015	343	4.5	1.66
(24)	The increasing importance of herbicides in worldwide crop production	Pest Management Science	2013	309	3.8	1.49
(25)	Soil erosion and surface runoff on different vegetation covers and slope gradients: a field experiment in Southern Shaanxi Province, China	Catena	2013	305	5.4	1.47
(26)	Nitrogen dynamics and budgets in a winter wheat-maize cropping system in the North China Plain	Field Crops Research	2003	304	5.6	1.91
(27)	Estimating crop yield potential at regional to national scales	Field Crops Research	2013	302	5.6	1.91
(28)	Productivity and sustainability of the rice-wheat cropping system in the Indo-Gangetic plains of the Indian subcontinent: problems, opportunities, and strategies	Advances in Agronomy	2012	301	9.265	1.12
(29)	Impacts of present and future climate variability on agriculture and forestry in the temperate regions: Europe	Climatic Change	2005	288	4.8	0.94
(30)	Soil mulching significantly enhances yields and water and nitrogen use efficiencies of maize and wheat: a meta-analysis	Scientific Reports	2015	275	3.8	1.05

JC, journal citations; JIF, journal impact factor; JCI, journal citation indicators