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Enhancing soil health and crop yields through water-fertilizer coupling technology

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Water-fertilizer coupling technology has emerged as a pivotal strategy in modern agriculture, recognized for its potential to enhance soil environmental quality, promote crop growth, and ensure sustainable resource utilization. With increasing global food demands and environmental concerns, optimizing agricultural practices is essential for achieving food security and ecological balance. This review aims to systematically review the direct impacts of water-fertilizer coupling on the physical, chemical, and biological properties of soil, while elucidating the underlying mechanisms that drive crop responses. Additionally, it evaluates the optimization of water-fertilizer coupling technology and its associated environmental benefits. The findings indicate that water-fertilizer coupling significantly improves soil structural stability, enhances microbial diversity, and increases soil enzyme activities. An appropriate water-fertilizer ratio markedly boosts soil microbial biomass carbon and nitrogen content, facilitating nutrient mineralization and accelerating the decomposition of organic matter. The implementation of intelligent water-fertilizer management systems has shown to enhance water use efficiency and reduce fertilizer loss rates, thereby minimizing the environmental footprint of agricultural production. The optimization of water-fertilizer coupling is crucial for improving soil health, crop yields, and resource efficiency. This technology not only supports sustainable agricultural practices but also contributes to national food security and rural revitalization efforts. Future research should focus on the interaction mechanisms among crops, soil, water, and fertilizer. It is essential to strengthen the development of water-fertilizer coupling regulation models and decision support systems to guide agricultural production practices effectively. Policymakers are encouraged to promote the adoption of integrated water-fertilizer management strategies to foster sustainable agricultural development and enhance environmental resilience. This review underscores the importance of advancing water-fertilizer coupling technology as a means to achieve sustainable agricultural productivity while safeguarding ecological integrity, aligning with the principles of socialism with Chinese characteristics.

KEYWORDS

water-fertilizer coupling, soil properties, environmental benefits, sustainable agriculture, intelligent management

1 Introduction

As the global population continues to rise, ensuring food security has become increasingly critical. Current agricultural practices often involve excessive irrigation and fertilization, leading to water wastage, soil degradation, and ecological deterioration (Wang, 2022). To harmonize food production with ecological sustainability, it is essential to explore new technologies and models that promote water conservation and enhance efficiency.

Water-fertilizer coupling technology optimizes water and fertilizer usage through precise control of irrigation and fertilization, significantly enhancing the efficiency of water and nutrient utilization in farmland (Wang et al., 2018). This approach reduces water and nutrient losses (Dou et al., 2022), improves soil physicochemical properties (Cheng et al., 2023), and increases crop yield and quality (Peng et al., 2023), and provides a conducive habitat for soil microbes (Gu et al., 2022). Adequate water-fertilizer matching elevates soil enzyme activities, promotes nutrient transformation and release, and strengthens soil fertility (Muhammad et al., 2022b).

The technology plays a crucial role in improving sustainable soil environments (Zhang et al., 2020). Integrated management significantly increases soil microbial biomass carbon and nitrogen content (Tuo et al., 2023) and enhances the soil's physical, chemical, and biological properties (Ding et al., 2020). Appropriate water and fertilizer rates boost activities of soil enzymes such as catalase, invertase, and urease (Li et al., 2010), which are vital for maintaining soil health and fertility (Zhang et al., 2024). Additionally, water-fertilizer coupling optimizes nutrient management, reduces fertilizer loss (Liang et al., 2023), and improves fertilizer utilization efficiency (Peng et al., 2023), achieving efficient use of agricultural resources (Liu et al., 2019).

Water-fertilizer coupling is valuable in enhancing crop yield and quality. Studies have shown that in potato production, reasonable integrated water and fertilizer management can significantly increase yield and improve quality indicators such as starch content (Zhang et al., 2023a). This improvement results from enhanced root development and increased nutrient absorption under the synergistic effects of water and fertilizer (Liu et al., 2015). Therefore, water-fertilizer coupling is essential not only for ensuring food security but also for increasing agricultural productivity and protecting the ecological environment.

This technology also plays an increasingly important role in reducing the use of chemical fertilizers and pesticides and controlling agricultural non-point source pollution. Precise irrigation and fertilization reduce excessive fertilizer application (Li H. et al., 2021), decreasing the risk of eutrophication in water bodies caused by nitrogen and phosphorus loss from farmland (Liu et al., 2021b). The application of fertigation improves the utilization efficiency of water and fertilizers, reduces irrigation water usage and chemical application intensity, and controls agricultural non-point source pollution at its source (Wang et al., 2021). This is significant for promoting clean agricultural production and fostering coordinated development between agriculture and the environment (Ma B. et al., 2024).

The impact mechanisms of water-fertilizer coupling on the soil environment are highly complex, involving aspects of soil physics, chemistry, and biology (Zhu et al., 2018). Effects vary significantly under different soil types, crop varieties, and climatic conditions (Jiang et al., 2024). An in-depth study of these impacts and the optimization of water-fertilizer management measures are of great significance for ensuring food security and improving the ecological environment of farmland.

In light of these insights, this study systematically reviews the impact of water-fertilizer coupling on the soil environment, with a focus on the physical, chemical, and biological properties of soil. It also explores optimization strategies for enhancing water conservation and efficiency, alongside future research directions. Water-fertilizer coupling is a multifaceted technology that necessitates cross-disciplinary collaboration among agriculture, water management, environmental science, and biology. Future research should prioritize interdisciplinary integration, the development of multi-scale and multi-factor simulation and prediction models, and the establishment of theoretical frameworks and decision-making tools for precise water-fertilizer management. Furthermore, it is essential to accelerate the development and deployment of advanced water-saving irrigation and precision fertilization equipment to enhance the automation and intelligence of water-fertilizer coupling technologies. Strengthening policies and regulations related to water-fertilizer management, improving agricultural subsidies and incentives, and encouraging farmers to adopt advanced technologies are also critical. Overall, water-fertilizer coupling technology plays an indispensable role in promoting sustainable soil environments, optimizing agricultural resource allocation, increasing crop yield and quality, and mitigating agricultural non-point source pollution. As precision agriculture and information technology continue to advance, intelligent integrated water-fertilizer management models will address current challenges, providing robust scientific and technological support for ensuring national food security and fostering resource-efficient, environmentally friendly agriculture.

2 Coupling of water and fertilizer with soil environment

2.1 Direct effects of water and fertilizer on soil environment

Water-fertilizer coupling, involving both irrigation and fertilization, has complex effects on soil physical properties. Irrigation alters soil moisture status, impacting hydraulic properties (Nolz et al., 2016), and water movement affects solute migration and distribution within the soil profile (Wang et al., 2017). Nutrient adsorption and release can modify soil aggregate structure and pore distribution (Ding et al., 2020). Changes in water and fertilizer availability also influence soil microbial activity and abundance, affecting the decomposition of organic matter and humus formation, which in turn alter soil structure (Tian et al., 2016).

Under water-fertilizer coupling, soil moisture undergoes dynamic changes (Liu et al., 2021a). Irrigation increases soil water content, reduces pore water pressure, and alters the soil water potential gradient, leading to moisture redistribution within the soil profile (Lu et al., 2020). Plant root uptake and transpiration further influence soil moisture consumption and movement (Thomas et al., 2024). These dynamic changes directly affect the soil's water-holding capacity, storage, and available water content (Zhang Y.-W. et al., 2021). Moreover, variations in soil moisture affect temperature fluctuations and heat conduction, influencing crop growth (Calleja-Cabrera et al., 2020).

The water-fertilizer ratio is a critical factor affecting soil physical properties. An appropriate ratio can improve soil structure, enhance aggregate stability, and increase macroporosity, thereby promoting root growth (An et al., 2022). However, excessive water and fertilizer can lead to soil compaction, runoff, and nutrient leaching (Liu et al., 2021b). Optimizing the water-fertilizer ratio is essential for maintaining favorable soil physical conditions. Generally, a moderately low ratio is more conducive to maintaining soil structural stability and promoting root development (Romero et al., 2022).

Overall, water-fertilizer coupling has multifaceted impacts on soil physical properties. Proper management can optimize soil moisture conditions, improve soil structure, and create a favorable physical environment for crop growth. Monitoring the dynamic characteristics of water-fertilizer coupling effects and implementing targeted irrigation and fertilization strategies are crucial for sustainable soil utilization. Future research should focus on understanding the mechanisms of soil physical processes to provide a theoretical and technical basis for scientific water-fertilizer management plans.

Water-fertilizer coupling significantly affects soil chemical properties. An appropriate water-fertilizer ratio can enhance soil enzyme activity, promoting water and fertilizer conservation while protecting the soil environment and ecology (Ren et al., 2020). Optimal ratios have been shown to significantly improve soil invertase and urease activities, whereas excessively high ratios may reduce enzyme activity (Xiao et al., 2021). Phosphatase activity tends to increase with the water-fertilizer ratio (Antonious et al., 2020). Increased irrigation can significantly enhance soil alkaline phosphatase and dehydrogenase activities, while acid phosphatase activity in the topsoil increases markedly (Jat et al., 2024). Reducing fertilizer application while increasing irrigation can maximize enzyme activity (Muhammad et al., 2022a).

Water-fertilizer coupling also affects soil pH and electrical conductivity (EC). Fertilization can alter soil pH following certain patterns (Li et al., 2022). EC is closely related to nutrient ion concentration and reflects soil nutrient status (Ren H. et al., 2021). Soil pH influences microbial activity, which in turn affects nutrient transformation and availability (Philippot et al., 2024).

Furthermore, water-fertilizer coupling impacts the content and distribution of essential soil nutrients, which exhibit gradient distribution in the soil profile, reflecting spatial heterogeneity (Lu et al., 2023). The efficiency of crop nutrient uptake is closely related to soil fertility (Zhang et al., 2010). Additionally, water-fertilizer coupling influences soil organic matter content and microbial community activity (Shao et al., 2019). Combining organic and inorganic fertilizers can significantly enhance soil organic matter, improving soil quality (Wei et al., 2016). Microbial activity indicators, such as soil enzyme activity, are crucial for assessing soil quality and are closely related to fertility (Meena et al., 2024).

The soil environment is a dynamic and complex system where physical, chemical, and biological processes interact intricately. Increasing water-fertilizer rates significantly enhances soil enzyme activities. For instance, the T2 (nitrogen was reduced by 20%) treatment resulted in increases of 45.59% in catalase activity, 72.57% in urease activity, and 78.23% in sucrase activity within the 0–20 cm soil layer (Yao et al., 2024). Similarly, the T5 treatment (80% evapotranspiration (ETc), 180–90–225 kg ha^{-1}, Qingshu 9) optimally enhanced potato yield to 49,222.3 kg ha^{-1} and significantly improved soil urease and catalase activities by 7.04 and 9.62%, respectively (Zhang et al., 2023b).

Nitrogen fertilization increases soil microbial biomass carbon by 17% and enhances dissolved organic carbon by 25%, while simultaneously reducing microbial diversity by up to 17% (Yang et al., 2022a). This illustrates the complex interactions and potential ecological trade-offs associated with water-fertilizer coupling strategies. The impact of water-fertilizer rates on soil enzyme activities is intricately dependent on the stages of crop rotation. Variations in soil pH and fertilization practices, particularly during the wheat stage, significantly influence microbial nitrogen and phosphorus limitations as well as enzymatic stoichiometry (Xie et al., 2022). Organic fertilization treatments significantly enhance soil organic carbon by 79–104%, increase available phosphorus by 26–36 times, and boost β-glucosidase activities by 161–171%, as well as alkaline phosphomonoesterase activities by 75–91% (Wang et al., 2024b). Investigating the dynamic patterns of these indicators helps elucidate the mechanisms by which water-fertilizer coupling affects the soil environment. Future research should intensify quantitative analysis of the relationships between water-fertilizer rates, irrigation patterns, and soil biological processes to optimize management strategies and promote agricultural soil health.

The application of water and fertilizers significantly influences ion concentrations in soil solutions, thereby affecting chemical properties such as pH and salinity. Notably, salinity and sodicity impact more than 25% of total land and 33% of irrigated land worldwide, posing considerable risks to soil fertility, groundwater quality, and food security (Mohanavelu et al., 2021). Optimizing the coupling of water and nitrogen—specifically through irrigation at 2,000 m^3 ha^{-1} and the application of 210 kg ha^{-1} of nitrogen—stabilizes soil microbial diversity and enhances the abundance of nitrogen-fixing bacteria. Irrigation predominantly influences bacterial communities, while nitrogen application affects fungal populations (Yang H. et al., 2022). Efficient management of water-fertilizer coupling, particularly through the application of nanofertilizers, significantly enhances nutrient cycling. This process promotes the mineralization and nitrification of nitrogen, phosphorus, and potassium, increasing the availability of soil nutrients and improving crop nutrient uptake while minimizing environmental pollution (Yahaya et al., 2023). A 10-year study demonstrates that conservation tillage rotation enhances soil structure and nutrient content, leading to increases in soil porosity by 3.2–6.7% and macroaggregate content by 35.2–46.4% (Zhang Y. et al., 2021). The plant root system serves as the nexus of material and energy exchange in the soil–plant system and is a primary mediator of the soil environment's response to water-fertilizer coupling. Water and fertilizer conditions significantly influence root growth and phosphorus uptake. Pre-sowing irrigation combined with surface fertilization (W80F10) increases root length by up to 11.1% in the 0–20 cm soil layer and enhances root acid phosphatase activity by up to 14.4% in the 0–40 cm and 60–80 cm soil layers (Chen et al., 2020).

2.2 Progress of water-fertilizer coupling technology

Advancements in modern water-saving irrigation technologies have introduced innovative methods to agricultural production. Drip irrigation, a highly efficient micro-irrigation technique, enables precise water and fertilizer management, resulting in significant benefits such as water conservation, reduced fertilizer usage, and enhanced crop yield and quality. When integrated with fertilization devices, drip irrigation systems facilitate fertigation by delivering water and nutrients directly to the crop root zone, thereby increasing fertilizer use efficiency and mitigating the risks of non-point source pollution.

Optimizing drip irrigation system parameters—including emitter layout, pipe diameter, and irrigation scheduling—can further enhance performance. Implementing a novel multi-level optimization framework for subsurface drip irrigation systems, for instance, can increase water productivity by up to 30% and profitability by 27% (Seidel et al., 2015). Minimizing deep percolation and surface evaporation while enhancing water use efficiency significantly improves irrigation practices. Studies have shown that 53.2% of irrigation water in cotton fields is lost to deep percolation, underscoring the urgent need for optimized strategies to ensure sustainable water resource utilization in arid regions (Li et al., 2016). The growth of information technology has propelled the development of smart irrigation systems, emerging as a new trend in water-saving irrigation (Sidhu et al., 2021). Utilizing wireless sensor networks and the Internet of Things (IoT), these systems monitor soil moisture, temperature, and conductivity in real time, dynamically adjust irrigation strategies based on crop growth models and meteorological data, and automate irrigation control (Figure 1). The integration of big data analytics and machine learning algorithms into precision agriculture refines irrigation decisions, accurately forecasts crop water requirements, and provides early warnings for drought and pest risks (Sishodia et al., 2020).

Precision water control technologies have garnered considerable attention for their role in enhancing irrigation efficiency. Monitoring physiological indicators—such as plant canopy temperature, stem flow, and soil moisture dynamics—enables precise estimations of crop transpiration, aiding in determining optimal irrigation timing and quantities. In a vineyard setting, a sensor fusion approach combined with a boosted regression trees algorithm achieved a correlation coefficient of 0.9 and a 12% error rate in predicting stem water potential (Ohana-Levi et al., 2022). Variable rate irrigation technology, which adjusts water applications dynamically according to different stages of crop growth, significantly enhances water use efficiency. This method addresses the growing demand for freshwater and mitigates drought effects, demonstrated by the superior performance of closed-loop control systems that integrate monitoring of soil, plant, and weather conditions (Bwambale et al., 2022). Additionally, precision water control not only improves water use efficiency but also significantly reduces methane emissions. Effective management of water-fertilizer coupling can lead to reductions of up to 67.27% in methane emissions, improve soil water-thermal conditions, promote root development, and increase both crop resilience and yield in rice paddies (Ma N. et al., 2024).

Advancements in fertilization technology play a critical role in enhancing agricultural productivity while protecting the ecological environment. A balanced combination of quick-acting and slow-release fertilizers—specifically formulations containing 30–50% controlled-release nitrogen—can reduce nitrogen application by 25% without compromising grain yield (Hu et al., 2023). Controlled-release fertilizers, utilizing polymer coatings or slow-release agents, effectively delay nutrient release to align with crop uptake, reducing fertilizer loss, enhancing nutrient use efficiency, mitigating environmental impacts, and supporting sustainable agricultural practices (Kassem et al., 2024). The combined use of organic and inorganic fertilizers represents a vital direction in fertilizer development. Replacing more than 50% of chemical nitrogen fertilizer with organic fertilizer significantly improves soil aggregate formation, microbial biomass, and enzyme activities in gravel-mulched fields (Tang C. et al., 2024). Notably, macroaggregates (>2 mm) exhibit higher microbial biomass carbon and nitrogen levels compared to microaggregates (<0.25 mm) ($p < 0.05$). The combined use of organic and inorganic fertilizers leverages their respective advantages,

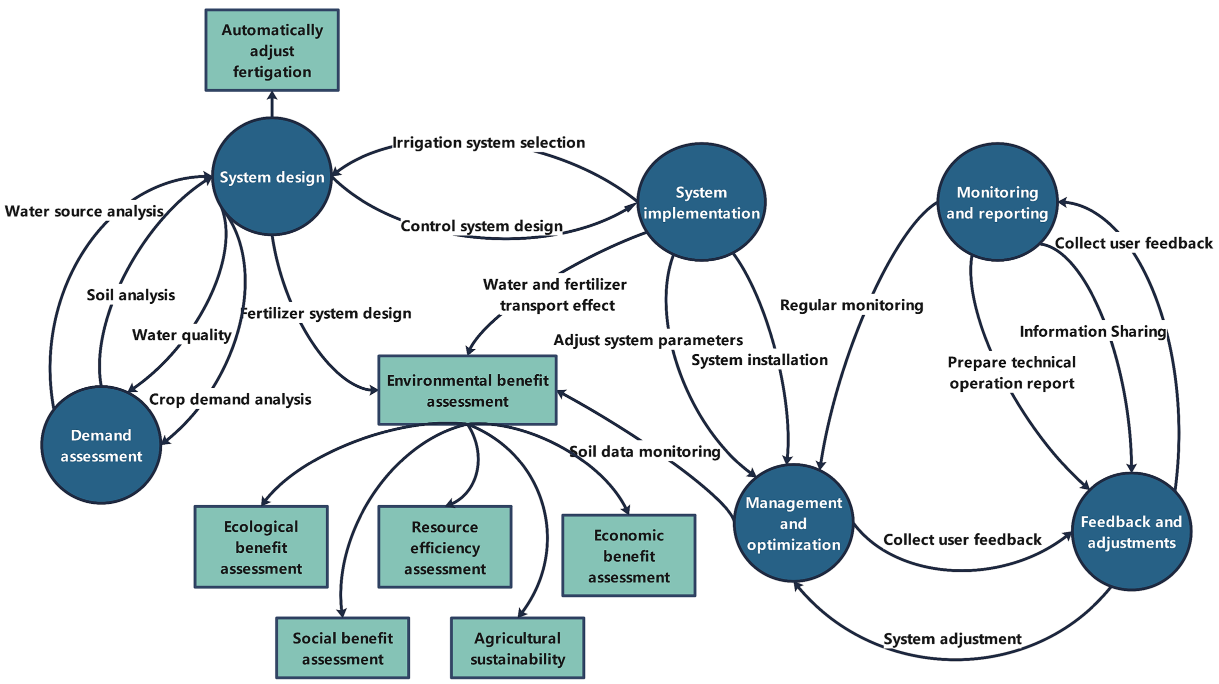

FIGURE 1
Flow chart for the optimization of water-fertilizer coupling technology and the evaluation of environmental benefits.

ultimately promoting crop growth and development (Bargaz et al., 2018). Deep-band placement of fertilizer at a depth of 25 cm significantly reduces gaseous nitrogen loss by up to 49.91%, increases nitrogen use efficiency by 38.37%, and enhances maize yield by 13.83% (Wu P. et al., 2021). Integrating soluble or liquid fertilizers with practices such as diversified crop rotations, no-till farming combined with organic mulches, and enhanced carbon-nitrogen-water cycling can significantly reduce fertilizer migration losses (Wang et al., 2024a). These strategies also improve soil health, nutrient efficiency, and the overall resilience of agroecosystems.

Integrated water and fertilizer technology combines irrigation and fertilization, allowing for the simultaneous and precise delivery of water and nutrients by dissolving fertilizers in irrigation water. This technique employs real-time soil moisture and nutrient sensors to monitor conditions, aligning with crop demand models to dynamically optimize irrigation and fertilization decisions, thereby enhancing water and fertilizer use efficiency (Figure 2). Utilizing an integrated system that combines variable-rate fertilizing devices with precision irrigation equipment can significantly reduce fertilizer leaching and water waste. This approach not only diminishes non-point source pollution but also improves the effectiveness of water quality management by leveraging real-time data from wireless sensor networks (Zia et al., 2013). An intelligent agricultural management platform has been established by integrating IoT and big data

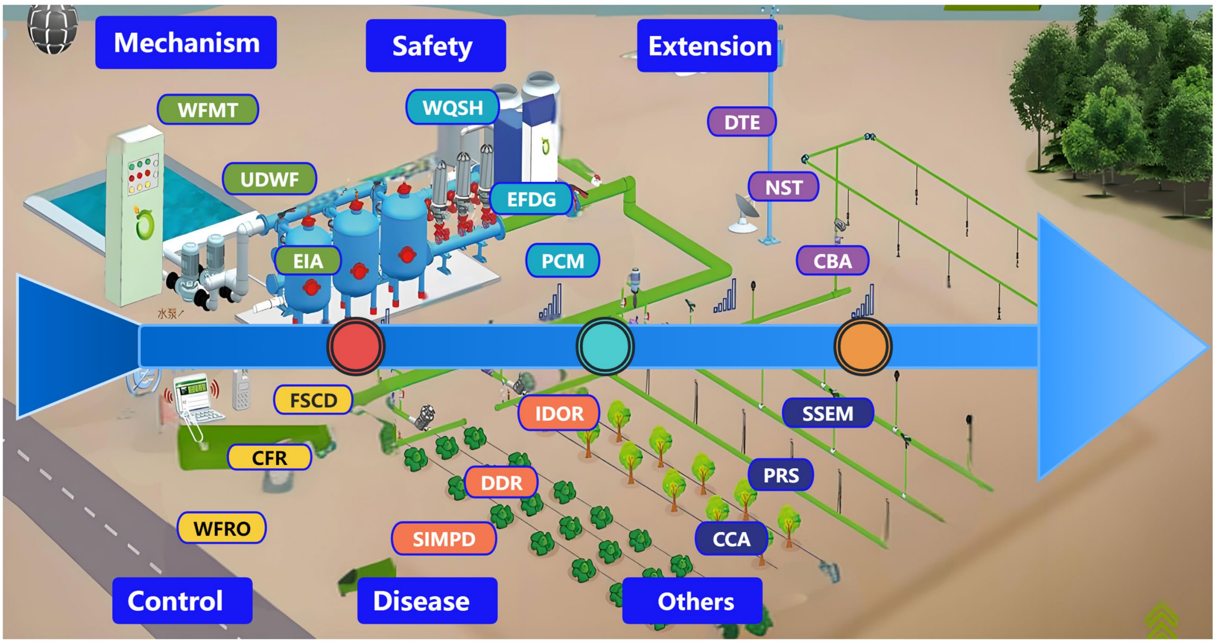

FIGURE 2
The scientific and technical problems to be solved in water and fertilizer integration technology. Mechanism: (1) WFMT (water and fertilizer migration and transformation), the model of water and fertilizer coupling relationship is not perfect, it is difficult to accurately describe the law of water and fertilizer migration and transformation, which affects the utilization of fertilizer and water resources. (2) UDWF (uneven distribution of water and fertilizer), uneven distribution of soil water leads to uneven distribution of fertility, which affects crop absorption and utilization. (3) EIA (environmental impact assessment), excessive use and improper management of fertilizers can lead to contamination of groundwater and surface water bodies. How to reduce the environmental impact, especially to prevent the loss and pollution of nitrogen, phosphorus and other elements, is a problem that needs to be solved. Control: (4) FSCD (difficult control fertilizer supply), traditional water and fertilizer integration technology is difficult to achieve accurate fertilizer supply, and it is easy to cause nutrient waste or insufficient. (5) CFR (crop fertilizer requirement), soil nutrient release rate does not match with crop fertilizer requirement, resulting in reduced fertilizer efficiency. (6) WFRO (water and fertilizer ratio optimization), the rule of water and fertilizer requirement of different crops was determined, and the optimal ratio of water and fertilizer was determined considering the ability of soil to absorb water and maintain fertilizer. Safety: (7) WQSH (water quality safety hazard), fertilizers used in the integrated water and fertilizer system may contain harmful substances such as residual pesticides and heavy metals, which pose a threat to water quality. (8) EFDG (excessive fertilization damage groundwater), excessive fertilization will lead to the accumulation of nutrients in the soil and damage the quality of groundwater. (9) PCM (precise control and monitoring), precise control of the amount of irrigation and fertilization is essential for integrated water and fertilizer technologies. Monitoring the dynamics of soil moisture, fertilizer concentrations, and plant water and nutrient requirements requires more precise and real-time technologies. Disease: (10) IDOR (increase disease occurrence risk), in an integrated water and fertilizer system, long-term irrigation and fertilization create an environment conducive to the growth of pathogenic bacteria and increase the risk of disease occurrence. (11) DDR (decreased disease resistance), excessive fertilization leads to crop growth and decreased disease resistance. (12) SIMPD (system intelligent monitoring of pests and diseases), integrate sensors and information technology to realize automatic and intelligent operation and monitoring of the integrated water and fertilizer system. Extension: (13) DTE (difficulty in technology extension), the technology of water and fertilizer integration involves many disciplines, has a high degree of technical integration, and is difficult to popularize. (14) NST (need specialized training), farmers need specialized training in order to become proficient in technology. (15) CBA (cost benefit analysis), the initial investment and operating costs of integrated water and fertilizer technology are high, and farmers and ranchers need to know whether the technology can bring sufficient economic benefits. Others: (16) SSEM (standardized systematic evaluation and monitoring), the lack of standardized systematic evaluation and monitoring methods makes it difficult to evaluate the effect of technology promotion. (17) PRS (policy and regulatory support), appropriate policy and regulatory frameworks can promote the application and development of integrated water and fertilizer technologies, the lack of which may be an obstacle to technology roll-out. (18) CCA (climate change adaptation), as the impact of climate change intensifies, how to adapt integrated water and fertilizer technologies to changing climatic conditions is a challenge that needs to be addressed.

analytics. This platform enhances crop yield, optimizes resource utilization, and reduces operational costs through precise and automated monitoring and control of farming activities (Rehman et al., 2022). By deploying wireless sensor networks to collect real-time data on soil, crops, and environmental conditions, and integrating this information with an agronomic knowledge base and machine learning algorithms, the system provides diagnostic warnings and dynamic prescriptions for irrigation and fertilization (Paul et al., 2022). Farmers can monitor field conditions remotely via mobile devices, optimize management decisions, and achieve precision agriculture. Moreover, data mining and analysis refine irrigation and fertilization models, guiding farmers to improve management practices and promoting the standardization and scaling of agricultural production.

The application of integrated water and fertilizer technology significantly enhances agricultural production efficiency and product quality while yielding substantial benefits in energy savings and emission reductions. For instance, the chance-constrained possibilistic mean–variance multi-objective programming model optimizes water resource management under diverse hydrological conditions (Wu H. et al., 2021). The traditional separation of irrigation and fertilization has resulted in spatiotemporal mismatches, with 49.09–63.64% of cities in the North China Plain applying fertilizers at rates below the regional average (Yu et al., 2022). Optimization of fertigation techniques led to a reduction in nitrate leaching to 7.1% and an increase in plant uptake to 73.5% (Azad et al., 2018), illustrating the potential to minimize groundwater contamination and conserve resources through precise management of water and fertilizer applications. The precise management facilitated by the Integrated Optimization Decision System has enhanced system benefits by up to 96.10% and reduced nitrogen loading by up to 623.16%, effectively addressing agricultural non-point source pollution (Xu et al., 2023). The integration of artificial intelligence with fertigation equipment can reduce field operations by up to 50% (Chen et al., 2023).

2.3 Water-fertilizer coupling and soil environmental assessment

Assessing soil environmental quality is essential for accurately understanding the health of soil ecosystems. The Triad approach, which integrates chemistry, ecotoxicology, and ecology, revealed a range of integrated risk levels (0.24–0.85) across various sites (Hong et al., 2021). This underscores the necessity for comprehensive, site-specific evaluations and highlights the potential of the Triad method to enhance traditional ecological risk assessments for the effective management of heavy metal-contaminated soils, providing a scientific basis for soil environmental management.

By integrating coefficient of variation analysis with a comprehensive soil quality assessment system, significant polycyclic aromatic hydrocarbon (PAH) pollution was identified in the surface soil of Shougang Steel, with concentrations reaching up to 53.8% from backfill sources (Sun et al., 2024). This finding emphasizes the need for multifaceted soil environmental assessments to accurately represent overall soil quality. Soil organic matter, stratum, and weathering coefficient significantly influenced total selenium (Se) levels (median: 0.308 mg kg^{-1}) and bioavailable Se (mean: 12.2%) (Liu Y. et al., 2024). In the Qilian Mountains, a study revealed significant declines in soil organic matter (from 45.80 to 12.70 g kg^{-1}) and plant cover (from 85.5 to 6.0%) associated with increasing desertification (Liu Z. et al., 2024). These findings underscore the urgent need for targeted prevention and remediation strategies to preserve soil functions in semi-arid alpine regions.

The future of soil environmental assessment lies in integrating various methods and multi-source data—such as soil physicochemical properties, contamination status, and biodiversity—to develop comprehensive assessment models. Enhancing Groundwater Vulnerability Assessment (GWVA) by incorporating land use and adjusting parameter rates increased the Pearson correlation with measured nitrate concentrations from 0.42 to 0.75 (Abduljaleel et al., 2024). Agricultural soils in Wenzhou face moderate to significant ecological risks, primarily due to cadmium (Cd) and lead (Pb). Scenario simulations indicated a reduction in risks under optimistic scenarios, while default scenarios projected increased risks (Xia et al., 2024). To evaluate the effects of water-fertilizer coupling, crop growth simulation models and fertilizer balance algorithms have been developed. These models consider the impact of water and fertilizer on the soil environment and crop growth, allowing for a quantitative assessment of the effectiveness and sustainability of water and fertilizer management practices.

Using material flow analysis (MFA) and life cycle assessment (LCA) methods, the environmental benefits of water-fertilizer coupling technology were evaluated (Figure 3). Field experiments demonstrated that the application of 5–6 t ha^{-1} of compost or 6 t ha^{-1} of maize stover, in conjunction with *Bacillus subtilis*, significantly improved soil properties and enhanced crop growth (Zhang W. et al., 2022). This approach increased water-fertilizer productivity by up to 30% under arid conditions, highlighting the potential of organic amendments for sustainable agriculture. These findings enable the simulation of changes in crop yield, quality, and soil nutrient dynamics under different water and fertilizer treatments, ultimately optimizing irrigation and fertilization strategies.

Substance flow analyses indicated that Huantai County experienced substantial annual nutrient inputs, averaging 696 kg N ha^{-1}, 104 kg P ha^{-1}, and 300 kg K ha^{-1} from 2010 to 2014 (Bellarby et al., 2018). A comprehensive irrigation efficiency evaluation system and soil environmental monitoring indicators are needed. The irrigation district scale, characterized by water use efficiency and water productivity values ranging from 0.1 to 0.85 and 0.08 to 0.8 kg m^{-3}, respectively, is identified as the most suitable management scale for addressing water resource utilization challenges in arid river basins (Zhou et al., 2021). Soil environmental monitoring, which examines changes in physicochemical properties such as salinization, pH, and organic matter content due to varying water and fertilizer conditions, is crucial for assessing and mitigating ecological impacts on agroecosystems (Ondrasek and Rengel, 2021). Therefore, a comprehensive model that analyzes crop yield, soil fertility, and irrigation benefits is necessary for integrated water and fertilizer management in agriculture.

Enhancing theoretical and methodological research on the effects of water-fertilizer coupling is crucial for mitigating resource scarcity and environmental pollution in agriculture. The application of the FIC-GIQMP model in the Shiyang River Basin exemplifies this importance, achieving a 17.89% increase in net benefits along with significant reductions in carbon (47.99%) and water (32.11%) footprints, thereby promoting sustainable agricultural development (Xu et al., 2022). Principal Component Analysis (PCA) enables

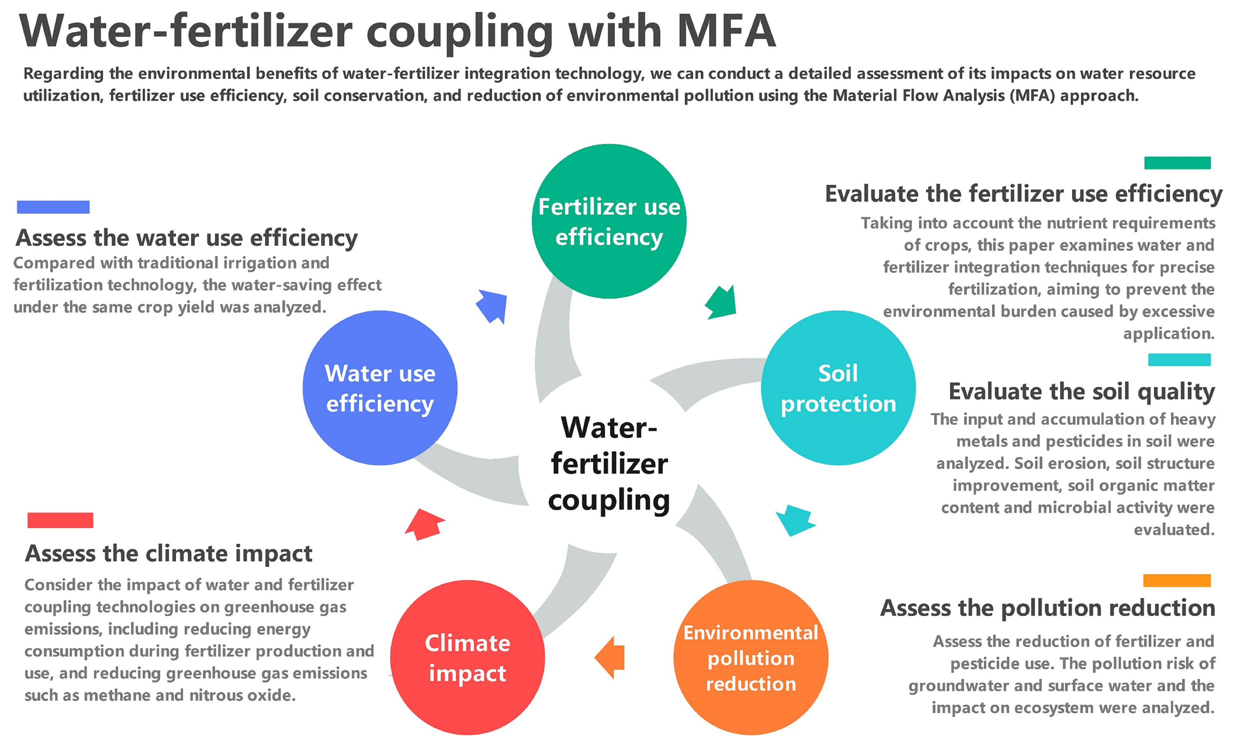

FIGURE 3
Environmental benefits of water and fertilizer coupling technology in material flow analysis (MFA).

researchers to identify key factors influencing the soil environment, such as irrigation levels, fertilization intensity, and crop types. For example, the T4 treatment in a study (80% evapotranspiration (ETc), dripper discharge rate of 3 L h^{-1}, and 180 kg N ha^{-1}) optimized potato yield, quality, irrigation water use efficiency, and partial factor productivity in sandy loam soil. This treatment resulted in a 23.9% increase in yield and a 60% enhancement in vitamin C content compared to lower fertilizer rates (Wang et al., 2020). Analysis of Variance (ANOVA) is utilized to assess the significance of differences among treatment groups, providing a basis for optimizing water and fertilizer management strategies. In the Three-River Headwaters Basin (TRHB), provisioning and regulating services have increased over a 20-year period, revealing significant spatiotemporal variations that inform targeted watershed management and protection efforts (Wang J. et al., 2022).

Data Envelopment Analysis (DEA), a linear programming-based method for evaluating efficiency, has been extensively applied in agriculture. Management practices have a more pronounced influence on water use efficiency than the types of irrigation systems employed. Additionally, younger farmers and larger farms generally exhibit lower levels of excess irrigation water usage (Lilienfeld and Asmild, 2007). The observed eco-inefficiency among Spanish rain-fed farmers is primarily attributed to technical inefficiencies in input management. Furthermore, education and participation in agri-environmental programs significantly enhance eco-efficiency (Picazo-Tadeo et al., 2011). DEA can also be integrated with other quantitative methods, such as Life Cycle Assessment (LCA), to conduct comprehensive environmental-economic assessments of water and fertilizer management (Figure 4). Multivariate statistical analysis is a robust tool for elucidating intricate relationships among multiple variables. For instance, deficit drip irrigation at 75% of ETc, combined with an application of 170 kg N ha^{-1}, optimized grain yield, water use efficiency, and nitrogen use efficiency in winter wheat. Over 65% of the increased yield was attributable to nitrogen application, while approximately 20% was due to irrigation (Lu et al., 2021).

Gray relational analysis, suitable for analyzing systems with small samples and high uncertainty, determines the influence of various factors on system behavior by calculating their gray relational degree. In water-fertilizer coupling research, this model investigates the relationships between irrigation and fertilization practices and their effects on soil nutrient dynamics and crop growth. For example, the optimal combination of 653.7 m^3 ha^{-1} of irrigation, 1,141.9 kg ha^{-1} of nitrogen, and 422.1 kg ha^{-1} of magnesium maximized cucumber yield (88,412.6 kg ha^{-1}), quality, and nutrient use efficiency in Northwest China (Li J. et al., 2023). By incorporating fuzzy mathematical methods, gray relational analysis can contribute to developing water-fertilizer decision support systems, enhancing the intelligence of agricultural production. Moreover, integrating Knowledge-Based Engineering (KBE) and web crawler technology advances intelligent irrigation, optimizing decision-making processes and improving the efficiency of water and fertilizer use in agriculture (Zhai et al., 2021). Response Surface Methodology (RSM), an optimization technique employing experimental design and mathematical modeling, is extensively applied in water-fertilizer coupling research. An optimal combination of 76% field capacity, 52.0 mg kg^{-1} nitrogen, and 49.0 mg kg^{-1} phosphorus maximized the growth and physiological performance of *Amorpha fruticosa* in coal-spoiled soils (Roy et al., 2020).

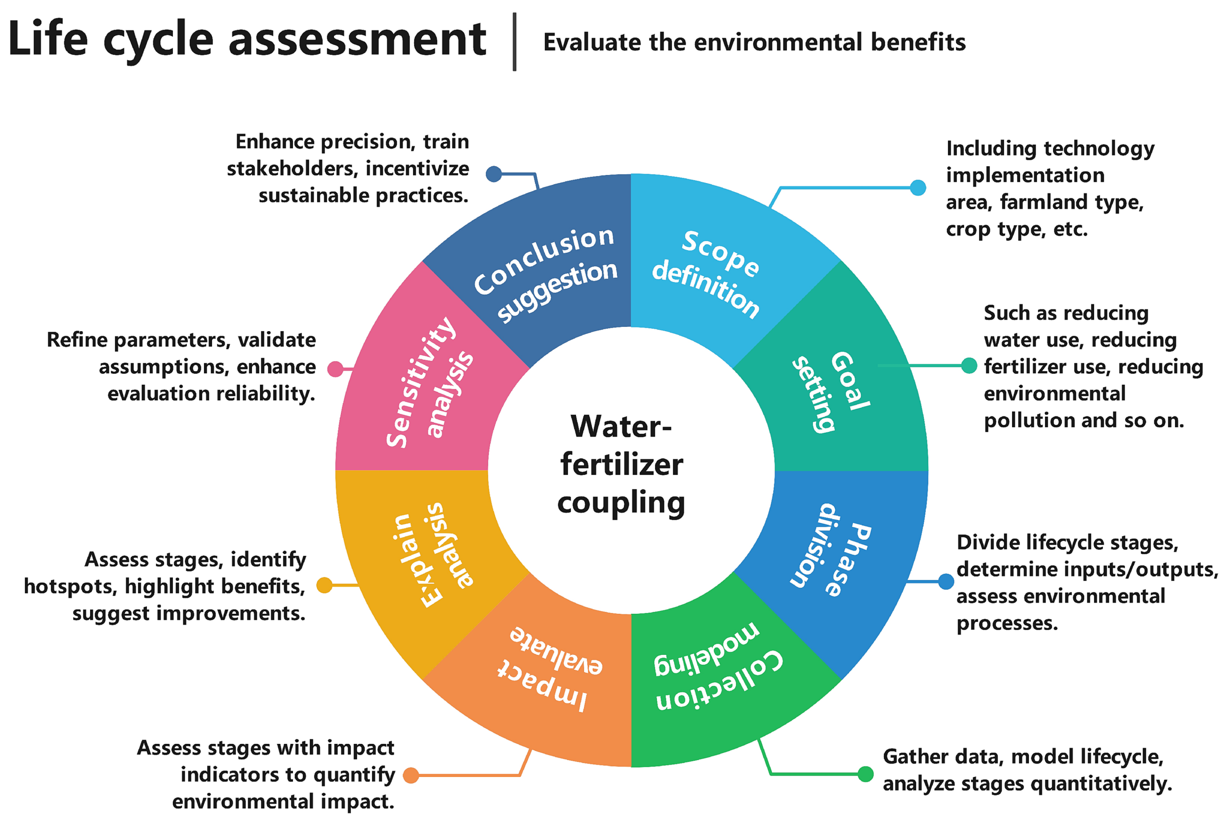

FIGURE 4
The life cycle assessment (LCA) method was used to evaluate the environmental benefits of water and fertilizer coupling technology.

3 Coupling of water and fertilizer to soil physical properties

3.1 Soil water dynamics

Soil moisture is a critical factor affecting crop growth and yield, and integrated water-fertilizer technologies significantly improve soil moisture conditions by enhancing the soil's water retention capacity. For instance, applying soil amendments like biochar and polyacrylamide at a rate of 8.3 g kg^{-1} can improve soil aggregate stability by 188% and increase soil water retention by 128.9%. These improvements boost the dry weight of beans and maize by 92.9 and 146.4%, respectively (Kang et al., 2022). The combined application of chemical and organic fertilizers enhances soil water storage and improves soil moisture utilization efficiency. A meta-analysis demonstrates that these practices can increase soil organic matter by up to 55.38%, total nitrogen by 56.39%, and maize yield by as much as 220.42% (Jiang et al., 2024). This effectiveness is primarily due to the optimization of irrigation and fertilization methods, which reduces ineffective evaporation and deep percolation (Li et al., 2016), thereby retaining more moisture in the root zone for crop absorption (Wu et al., 2022).

The impact of integrated water-fertilizer technologies on soil moisture dynamics exhibits notable temporal variability throughout the crop growth stages (Table 1). Soil moisture conditions demonstrate distinct trends at different phases. For example, applying orthophosphate fertilizers at an adequate water level of 75% field capacity significantly enhances chickpea growth, nutrient uptake, and use efficiency, resulting in improvements in biomass accumulation and the photosynthetic performance index by up to 25% (Chtouki et al., 2022). Combining biochar addition with daily fertigation significantly improves the soil quality index, leading to the highest cucumber yields and enhanced water-fertilizer productivity. Specifically, irrigation water productivity reached 557.9 kg mm^{-1}, and partial factor productivity showed notable improvement over a two-year period (Zhang et al., 2020). Micro-moistening irrigation, coupled with a moderate fertilization rate of 18.6 g per plant, significantly enhances the growth of young mango trees, achieving the highest water-fertilizer use efficiency and total dry mass, which are 2.58 and 2.32 times greater than those obtained through traditional methods (Li Y. et al., 2021). By the maturation stage, soil moisture gradually recovers. Integrated water-fertilizer technology maintains soil moisture within an optimal range throughout various growth stages by real-time monitoring and dynamically adjusting irrigation and fertilization (Kang et al., 2021).

The water-fertilizer rate is a significant determinant of the dynamic changes in soil moisture. Regulated deficit irrigation at maturity stage, when combined with moderate fertilization at a rate of 103.2 kg ha^{-1}, led to a 15% increase in mango yield compared to full irrigation. Additionally, water use efficiency improved by 20%, suggesting that this approach offers a sustainable water-fertilizer management strategy for dry-hot regions (Peng et al., 2023). The combination of biochar and biocompost significantly enhances the soil's water retention capacity, with the highest values observed in

TABLE 1 Temporal variability of soil moisture dynamics under integrated water-fertilizer technologies across crop growth stages.

Crop growth stage	Impact on soil moisture dynamics	Notes	References
Germination	Optimized soil moisture levels: Integrated technologies provide precise water application, ensuring optimal moisture for seed germination.	Prevents soil crusting and promotes uniform seed emergence; Enhances early root development.	Jarrar et al. (2023)
Seedling stage	Improved moisture retention: Balanced fertilization enhances soil structure, aiding moisture retention during this critical growth phase.	Supports delicate seedlings by maintaining consistent moisture; Reduces evaporation losses.	Li X. et al. (2024)
Vegetative growth	Enhanced water availability: Adjusted irrigation schedules meet increased water demand, preventing water stress during rapid biomass accumulation.	Promotes vigorous vegetative growth; Nutrient availability is synchronized with water uptake.	Cui et al. (2009)
Reproductive stage	Stable moisture conditions: Minimizes temporal variability, ensuring consistent soil moisture during flowering and fruit set.	Crucial for pollination success and fruit development; Prevents drought stress that can reduce yield quality and quantity.	Bacelar et al. (2024)
Maturation	Controlled moisture reduction: Gradual decrease in soil moisture to facilitate crop maturation without inducing stress.	Helps in the accumulation of desirable traits (e.g., sugar content in sugarcane); Avoids issues like lodging due to excessive moisture.	Mehdi et al. (2024)
Post-harvest	Residual moisture management: Maintains adequate soil moisture for soil microbial activity and preparation for the next cropping cycle.	Aids in residue decomposition; Contributes to soil health restoration; Prepares the soil for subsequent planting or fallow periods.	Liu et al. (2024a)

treatments containing 6% biochar and either 3% or 6% biocompost, exceeding 0.7 g H_2O g^{-1} dry weight (El Moussaoui et al., 2024). This combination provides a resilient and sustainable alternative to traditional manure and chemical fertilizers for improving alfalfa productivity under water stress conditions. However, exceeding optimal water-fertilizer rates can lead to excessive moisture, poor soil aeration, and increased nutrient leaching, which are detrimental to crop absorption and utilization of water and fertilizers (Yang et al., 2023). An innovative approach optimized irrigation for eggplants by employing an interval of 4.56 days and a water salinity of 1.47 dS m^{-1} in an outdoor environment. This method resulted in a high yield of 2,490.7 g per plant and a water use efficiency of 3.32 g (plant·mm)$^{-1}$, demonstrating the effectiveness of multi-factor modeling in enhancing crop productivity and resource efficiency in irrigated agriculture (Mahmoodi-Eshkaftaki and Rafiee, 2020).

3.2 Soil density and porosity

Water-fertilizer coupling significantly affects soil physical properties, particularly soil density and porosity (Guo et al., 2022). Total soil porosity is a crucial indicator of soil quality, directly influencing aeration, water retention, and fertilizer supply capacity (Alkharabsheh et al., 2021). The combined application of nitrogen fertilizer with medium biochar (30.7 t ha^{-1}) under drip irrigation enhanced maize yield by up to 9.85%. It also improved irrigation water use efficiency (up to 5.94 kg kg^{-1}), fertilizer nitrogen use efficiency (up to 50.28 kg kg^{-1}), and increased soil organic matter by up to 19.42% (Wang et al., 2023). These findings underscore the potential of integrated water-fertilizer-biochar management. Optimal nitrogen fertilization at 168 kg N ha^{-1} maximized maize root mass, while reductions of 33 and 17% were observed under zero and excessive nitrogen conditions, respectively. This highlights the critical role of adequate nitrogen supply in root development. Additionally, newly developed predictive equations for the root-to-shoot ratio based on yield, such as the upper bound $R:S = e^{-1.5-0.04\times \text{yield}}$, have the potential to improve biophysical models (Ordóñez et al., 2021).

Macropore size is closely associated with water and fertilizer conditions. Macropores primarily affect soil aeration and drainage; excessive irrigation and fertilization can reduce soil macropores, leading to compaction and nutrient leaching (Hartmann and Six, 2023). Effective management of water and nutrients in arid soils enhances the distribution of soil macropores, facilitating nutrient movement and moisture transformation, which helps mitigate the impacts of climate change on crop productivity (Naorem et al., 2023). The critical pore radius has emerged as an accurate predictor of soil permeability ($R^2 = 0.838$, $p < 0.001$) across diverse tillage and cropping systems. Root growth significantly influences soil porosity, particularly in pore classes exceeding 200 μm, underscoring the importance of biological pores in enhancing soil permeability (Qian et al., 2024). A heterogeneous soil structure, characterized by a 50% increase in macropores at high compaction (1.55 g cm^{-3}), significantly enhanced pea shoot biomass by 65% (Giuliani et al., 2024). This demonstrates the species-dependent advantages of complex pore structures on plant growth, likely due to preferential root growth within macropores.

Optimized soil and fertilizer management practices, such as no-till cultivation combined with straw mulching and the application of leguminous green manure, increased wheat root length by 20.9% and root surface area by 11.0%. These enhancements improved soil water content by 4.3% and nitrate nitrogen content by 13.4%, highlighting the role of robust root growth in enhancing soil porosity and nutrient utilization. Additionally, a 10% reduction in nitrogen fertilizer sustained yields while increasing overall efficiencies (Wu et al., 2023).

The stability of soil aggregates is closely related to their pore size distribution. Smaller aggregates (1–2 mm) exhibit higher total porosity and more stable pore structures in grassland and forest soils, enhancing resistance to structural collapse when submerged (Menon et al., 2020). Appropriate moisture conditions facilitate the formation and maintenance of aggregates (Ren P. et al., 2021), while adequate fertilizer supply can enhance soil microbial activity (Dincă et al., 2022). This accelerates the decomposition and transformation of organic materials, providing binding substances for aggregate formation (Cotrufo and Lavallee, 2022). High manure application rates significantly increased soil aggregate-associated organic carbon and total nitrogen by 40–50%, and increased particulate organic matter by 20% compared to the control (Gautam et al., 2022).

3.3 Soil temperature and moisture

Integrating water, fertilizer, and air in drip irrigation systems significantly improves soil health. This approach increased dissolved oxygen by 14.05%, oxygen diffusion rate by 30.14%, and soil respiration rate by 53.74%. Microbial biomass showed the most pronounced response, rising by up to 50.18%, followed by enhancements in enzyme activity and soil aeration (Lei et al., 2022). Controlled irrigation combined with high rates of organic fertilizer optimized soil conditions, leading to a 2.7% increase in rice yield compared to the use of chemical fertilizers alone, and a 22% increase compared to no fertilization. Additionally, soil pH, total nitrogen, and nitrate nitrogen positively influenced yield, collectively accounting for 75% of the variance observed (Li Y. et al., 2024). Employing small-flow drip irrigation (less than $1\,L\,h^{-1}$) with frequent fertigation (every 7 days) enhanced summer maize yield and water-use efficiency by up to 13.3 and 8.0%, respectively (Ma et al., 2022).

Soil thermal conductivity is a crucial indicator of its thermal properties and significantly affects soil temperature dynamics (Li et al., 2019). Conservation tillage practices, such as no-till and strip-till, have been shown to markedly improve soil structure. These methods can increase moisture content by up to 20.42%, enhance macroaggregates by 34.07%, and raise soil organic matter by $6.48\,g\,kg^{-1}$. Consequently, maize yields have increased by 12.9 and 14.9% compared to conventional tillage, demonstrating enhanced soil quality and productivity in newly reclaimed cultivated land (Liu Z. et al., 2021). Appropriate water and fertilizer management fosters favorable soil structure, enhances thermal conductivity, accelerates soil heat transfer, and facilitates the regulation and maintenance of soil temperature (Hatfield et al., 2017). Soil moisture plays a critical role in the performance of Earth-Air Heat Exchangers; fluctuations in saturation conditions can impact exchanged energy by more than 40% (Lin et al., 2020). This underscores the necessity of maintaining optimal soil humidity to boost thermal conductivity and improve heat transfer efficiency.

Soil temperature and moisture exhibit pronounced diurnal fluctuations (Yu et al., 2020). During the day, strong solar radiation increases soil temperature due to higher heat absorption. In the grapevine cultivar Tempranillo, night-time transpiration (Enight) contributes significantly to total daily transpiration—accounting for 3% on days with ample soil water content and up to 35% during periods of low daytime transpiration and reduced soil moisture. The average Enight contribution is 12%, highlighting the importance of nocturnal water loss, particularly after sunset and from veraison to harvest (Montoro et al., 2020). Sub-surface drip irrigation (SSDI) at 80% ETc, combined with 80% of the recommended nitrogen dose and foliar applications of KNO_3 and $MgSO_4$, significantly enhanced both crop and water productivity in cotton–wheat cropping systems. This approach resulted in approximately 43.2% savings in irrigation water and a 20% reduction in fertilizer requirements compared to traditional flood irrigation, while maintaining yield and improving irrigation water productivity by about 46.1% (Kaur et al., 2024). In arid oasis regions, non-productive water losses in maize fields averaged 39%, peaking at 58%. Evapotranspiration losses were most pronounced during June and July, whereas infiltration losses were significant in April–May and August–September (Jiao et al., 2023). These findings highlight the potential for considerable water savings through optimized irrigation management. Effective water and fertilizer strategies contribute to a diurnal equilibrium of soil temperature and humidity, providing stable and optimal conditions for crop growth.

4 Coupling of water and fertilizer to soil chemistry

4.1 Soil pH and EC values

Soil pH and EC are critical indicators of soil chemical properties, directly influencing nutrient availability and microbial activity (Zhao et al., 2018). Long-term fertilization in apple orchards (1988–2016) significantly enhanced soil organic carbon (SOC), total nitrogen (TN), and available nutrients, with the NPKM (nitrogen-phosphorus-potassium plus manure) treatment showing the most substantial improvement. However, this practice also led to soil acidification; the NPK and NPKM treatments reduced soil pH by 1.04 and 0.74 units, respectively. This decline was primarily attributed to excessive nitrogen fertilizer application, resulting in net hydrogen ion (H^+) production rates as high as 136.8 kmol ha^{-1} $yr.^{-1}$ in the N900 treatment (Ge et al., 2018). Similarly, excessive nitrogen fertilization in greenhouse lettuce production increased soil acidity and salinity, leading to pH decreases of up to 1.06 units and EC increases of up to 0.68 mS cm^{-1}. This was mainly due to nitrification-induced proton loading, ranging from 14.3 to 58.2 kmol H^+ ha^{-1}, which substantially exceeded the 0.3–4.5% contribution from lettuce uptake (Han et al., 2015). These findings indicate that excessive nitrogen application can lead to significant soil acidification and salinization, negatively affecting soil health.

In citrus cultivation, traditional soil fertilization alone is inadequate for optimizing yield, especially under soil conditions characterized by a slightly alkaline pH range of 7.1–8.4 and low organic matter content (<0.86%). Foliar nutrient applications are essential to enhance nutrient management and address significant deficiencies of nitrogen (94%), iron (76%), and zinc (67%) in citrus leaves (Ahmad et al., 2022). Addressing soil salinization requires comprehensive strategies that integrate both traditional and modern methods to improve soil and plant properties (Sahab et al., 2021). The combined application of lime and magnesium fertilizer effectively mitigates soil acidification, increasing pomelo yield by up to 34.2%. This approach also enhances fruit quality, evidenced by a 7.2% higher edible rate and a 4.2% increase in total soluble solids, and boosts annual net income by 37.4%, demonstrating its potential for improving productivity and economic viability in acidic citrus orchards (Zhang S. et al., 2021). Adding lime, particularly in soils with low pH, organic matter, cation exchange capacity, and clay content, significantly raises soil pH and reduces cadmium accumulation in crops. Among lime amendments, calcium carbonate is the most effective in lowering shoot cadmium concentration (He et al., 2021).

The application of biogas slurry, especially at a substitution rate of 50%, significantly improves soil structure and fertility. This is evidenced by enhanced aggregate stability, increased water and nutrient retention, and optimal crop yields in the lime concretion soils of the North China Plain (Tang et al., 2022). Long-term integrated application of NPK fertilizers, crop residues, and lime in the acidic soils of South China has led to significant improvements in wheat and maize grain yields, nitrogen-use efficiency, and mitigation of soil acidification (Daba et al., 2021). Soil pH significantly influences microbial activity by affecting the abundance of organic phosphorus–mineralizing genes, impacting microbial diversity and potentially reducing crop yields (Wan et al., 2021). Deviations from the optimal pH range can inhibit microbial growth and metabolism, reducing biological activity (Zhao et al., 2020). For example, in acidic soils, bacterial populations are lower than fungal populations, and actinomycetes are nearly absent (Khangura et al., 2023). Therefore, agricultural practices should focus on long-term soil pH monitoring, adopt scientific water and fertilizer management, and foster a microbial-friendly environment to enhance soil biological activity and fertility.

4.2 Content and distribution of soil nutrient elements

Under conditions of water-fertilizer coupling, significant changes occur in the content and distribution of major soil nutrients. Studies have shown that integrating water and fertilizer increases the carbon and nitrogen content of soil microbial biomass, which initially rises during the growth period but declines to its lowest levels at maturity (Wei et al., 2022). In potato production, specific water-fertilizer treatments achieved an optimal balance of yield, quality, and resource efficiency. The W2F3V1 treatment (80% ET_C, 120–60–150 kg ha^{-1}, Feiurita) resulted in the highest partial factor productivity and starch content, while the W3F2V1 treatment (60% ET_C, 180–90–225 kg ha^{-1}, Feiurita) demonstrated the highest irrigation water use efficiency and vitamin C content. Both treatments enhanced key soil microbial activities, highlighting the potential of tailored water-fertilizer management strategies for sustainable potato production in arid regions (Xing et al., 2022). Soil nutrient content exhibits considerable variability across different layers, reflecting spatial heterogeneity. The combined application of organic and inorganic fertilizers increased soil organic matter by up to 22.81% during the wheat season and 16.81% during the maize season. This approach also enhanced total nitrogen levels by 105.72 and 50.27%, respectively, improved microbial diversity, and increased crop yields compared to the exclusive application of urea or manure alone (Yang et al., 2020).

Soil enzyme activity is a crucial indicator of soil fertility and quality. A combination of low irrigation (60% field capacity) and high nitrogen application (300 kg N ha^{-1}) significantly enhanced activities of enzymes such as acid phosphatase, acid invertase, β-glucosidase, catalase, cellulase, and urease (Muhammad et al., 2022b). This treatment also increased bacterial alpha and beta diversity, indicating improved nutrient utilization and a more balanced microbial community compared to high irrigation regimes. Tree species diversity influences soil enzyme activities as well. The combination of birch and pine positively affected carbon- and nitrogen-related enzyme activities at intermediate soil depths (15–30 cm), while increased water availability enhanced phosphorus-related enzyme activities in the upper layers (0–30 cm). However, lower water availability diminished the benefits of tree diversity, underscoring the critical role of water in sustaining soil microbial activity and nutrient cycling across different soil depths (Maxwell et al., 2020). These findings suggest that optimizing water-fertilizer rates is essential for maintaining soil health. Additionally, soil enzyme activity varies during different growth stages, necessitating targeted water-fertilizer management.

Crop nutrient uptake and utilization are closely related to soil nutrient status. A rational supply of water and fertilizer significantly improves crop absorption efficiency for nutrients like nitrogen, phosphorus, and potassium, thereby promoting growth and development (Wei et al., 2024). Compared to conventional cultivation, water-fertilizer integration technology has increased nitrogen, phosphorus, and potassium uptake in sugarcane by 9.99, 12.58, and 10.32%, respectively (Ren T. et al., 2021). This enhancement is largely due to the activation and increased availability of soil nutrients facilitated by water-fertilizer coupling, providing ample nutrition for crop growth (Yan et al., 2023). In summary, finding the optimal water-fertilizer rate is crucial for maintaining soil health, enhancing microbial and enzyme activities, and improving nutrient uptake and crop yields. Targeted optimization of water and fertilizer management is necessary to sustain soil fertility and promote efficient crop production.

4.3 Soil organic matter and microbial activity

Integrated water-fertilizer technology significantly impacts soil organic matter content and microbial activity. Innovative no-till seeding (INtS) technology has been shown to enhance wheat yield, nitrogen uptake, and nitrogen use efficiency by 27.2, 28.9, and 31.9%, respectively, compared to conventional rotary-till seeding. Furthermore, INtS has reduced fertilizer and straw nitrogen losses by up to 20.6% over five growing seasons, while decreasing carbon and nitrogen footprints by 26.8 and 19.1%, respectively (Liu M. et al., 2024). The integration of water, fertilizer, and air in drip irrigation significantly enhances soil health by increasing dissolved oxygen levels, oxygen diffusion, and respiration rates by 14.05, 30.14, and 53.74%, respectively. This method also elevates the activities of soil enzymes such as urease, catalase, and phosphatase by 22.83, 93.01, and 61.35%, respectively, while augmenting the biomass of bacteria, fungi, and actinomycetes by 49.06, 50.18, and 20.39%, respectively (Lei et al., 2022). The application of microbial organic fertilizer (MOF) at a rate of 2.4 t/ha significantly enhances soil moisture by up to 36.42% and improves water-holding capacity by up to 15.98%. It also increases the activities of soil enzymes—including urease by up to 100.5%, peroxidase by up to 148.5%, and invertase by up to 32.9%. These enhancements lead to a substantial increase in jujube yield of 19.22%, demonstrating an effective strategy for sustainable jujube production and the mitigation of desertification in southern Xinjiang (Shao et al., 2023).

Different water-fertilizer rates have varied effects on soil microbes and enzyme activities. An optimal substrate composition of vermicompost and coconut bran at a 5:1 ratio improved water retention by up to 5.80% and increased nitrogen-use efficiency. This composition also enhanced plant nitrogen and phosphorus uptake by 81.18 and 4.74%, respectively, while increasing urease and catalase activities. Consequently, strawberry yield and quality improved, with total yield and average fruit weight increasing by 22.98 and 36.22%, respectively, compared to the control group (Tang X. et al., 2024). The short-term co-application of 15–30% organic fertilizer alongside chemical fertilizers (OFCF1 and OFCF2) enhanced topsoil aggregate stability, reduced bulk density, and increased soil organic carbon. This practice also boosted key enzyme activities, such as sucrase and urease, by up to 28 and 35%, respectively, while promoting maize yield by up to 12% compared to the application of chemical fertilizers alone (Zhai et al., 2023). These findings suggest that moderate water and fertilizer inputs are crucial for maintaining soil health and microbial activity within integrated water-fertilizer management.

5 Coupling of water and fertilizer to soil biological properties

5.1 Soil microbial community structure

The application of integrated water and fertilizer irrigation technology has significantly altered the structure and composition of soil microbial communities (Li et al., 2014). Drip fertigation enhances crop yields by 12.0%, improves water productivity by 26.4%, and increases nitrogen use efficiency by 34.3%. It also reduces evapotranspiration by 11.3% and can potentially decrease water inputs by up to 22% and nitrogen inputs by up to 33% without compromising yield (Li H. et al., 2021). Under water deficit conditions (50% ETc), inoculation with beneficial microorganisms—specifically *Bacillus amyloliquefaciens* and *Azospirillum brasiliense*—resulted in a 35% increase in corn productivity, enhanced soil microbial activity, and a 93% increase in mineral nitrogen content compared to full irrigation (Araujo et al., 2023). These findings demonstrate the potential of beneficial microorganisms to mitigate the effects of drought stress, primarily due to the favorable soil ecological environment created by integrated water and fertilizer management, which promotes microbial proliferation (Tan et al., 2021). However, excessively high or low water-fertilizer rates may suppress microbial activity, leading to a decline in their populations (Tuo et al., 2023).

Integrated water and fertilizer management also markedly affects the proportions of bacterial and fungal communities within the soil (Wang et al., 2019). Metagenomic sequencing analysis has revealed that appropriate water-fertilizer rates can maintain the balance between bacteria and fungi, enhancing soil microbial diversity indices (Gupta et al., 2022). Drip fertigation surpasses traditional methods by improving yield, water productivity, and nitrogen use efficiency by 12.0, 26.4, and 34.3%, respectively. Furthermore, it reduces evapotranspiration by 11.3% and has the potential to further decrease water and nitrogen inputs by up to 22 and 33%, respectively, without compromising yield (Li H. et al., 2021). Irrigated soils in the Mediterranean region exhibited increases in Ca^{2+}, K^{+}, and Na^{+} by 25, 8, and 7%, respectively, from 2002 to 2012, alongside a 5% increase in pH. In contrast, rain-fed soils showed long-term increases in soil organic matter (SOM), pH, Ca^{2+}, Mg^{2+}, and K^{+} by 23, 8, 60, 21, and 193%, respectively, coupled with a 50% decrease in Na^{+} (Telo da Gama et al., 2021). These changes, attributed to climatic shifts from sub-humid to semi-arid conditions, underscore the necessity for improved soil management practices to enhance sustainability. Understanding nitrogen transformation processes in soil and implementing sustainable fertilization practices are crucial for maintaining soil health, minimizing environmental pollution, and ensuring long-term agricultural productivity (Grzyb et al., 2021). Consequently, the use of integrated water and fertilizer technology assists in cultivating a healthy soil microbial community structure (Jin et al., 2022).

Beyond microbial quantity and diversity, integrated water and fertilizer management impacts the functional activities of soil microbes (Wang C. et al., 2022). Research has shown that appropriate water-fertilizer rates can enhance soil enzyme activities such as catalases, transferases, and ureases, which play vital roles in soil organic matter decomposition and nutrient transformation (Yang et al., 2022b). Additionally, judicious water and fertilizer management practices can amplify the degradation potential of microbes, accelerating the removal of pollutants like pesticide residues and heavy metals, thereby improving soil environmental quality (Akhtar et al., 2021).

5.2 Soil biodiversity

Soil biodiversity is a critical indicator of soil health, serving as a barometer of ecosystem stability and a driver of soil fertility, nutrient cycling, and resilience to environmental stresses (Bhaduri et al., 2022). The optimization of irrigation and fertilization through water-fertilizer coupling techniques significantly impacts soil biotic community composition and activity (Li H. et al., 2021). Nitrogen fertilization has been shown to significantly influence soil microbial biomass and composition, with the highest microbial biomass recorded at 80 and 60% field capacity when nitrogen was applied at 20 and 40 $g\,N\,m^{-2}$ per year, respectively (Li W. et al., 2023). Notable shifts in microbial community structure and enzyme activities were also observed under these conditions, highlighting the importance of optimizing water-fertilizer rates to enhance soil microbial dynamics and nutrient cycling. Integrated water and fertilizer management practices enhance soil microbial diversity and abundance, fostering beneficial microbial groups such as actinobacteria and nitrifying bacteria, which are crucial for nutrient cycling and soil health (Sabir et al., 2021). Adequate moisture and fertilizer supply create favorable conditions for soil microbes, promoting the growth and proliferation of beneficial microorganisms (Vurukonda et al., 2024).

Integrated and conservation agricultural practices have been demonstrated to enhance the abundance of soil fauna, with populations of beetles and earthworms increasing by as much as 100% compared to conventional tillage (Mamabolo et al., 2024). Soil physicochemical properties, particularly the carbon-to-nitrogen (C:N) ratio and organic matter content, significantly influence overall fauna abundance and diversity, highlighting the interdependence of soil biodiversity and ecosystem multifunctionality. Under varying water and fertilizer rates, the density and diversity of small soil animals such as nematodes and mites exhibit distinct differences. A global meta-analysis revealed that organic nitrogen fertilization significantly increases the density of springtails, mites, and earthworms, as well as the biomass of earthworms, compared to conditions without fertilization (Betancur-Corredor et al., 2023). These findings indicate that adopting organic fertilization, tailored to site-specific nitrogen regimes, enhances soil fauna communities and overall ecosystem functioning. Moderate water and fertilizer supply enhances both the abundance and diversity indices of soil fauna, whereas excessive or insufficient inputs hinder their activity. Projected drought scenarios have been shown to significantly reduce the biodiversity and abundance of oribatid mites, particularly in soils with lower fertility (Watzinger et al., 2023), underscoring the necessity for adjusted fertilization regimes to mitigate adverse effects on soil fauna and overall ecosystem functioning. Additionally, the processes involved in plant selection modulate the impact of agricultural management on rhizosphere microbial communities. The interaction between management practices and plant root exudates significantly influences microbial diversity and nitrogen-cycling processes. Notably, the abundance of the *nosZ* gene, associated with denitrification, was found to be higher in organically managed systems (Schmidt et al., 2019), underscoring the intricate relationship between management practices, rhizosphere microbiomes, and soil health.

Optimizing water and fertilizer management is vital for sustaining soil biodiversity and promoting ecosystem health (Shah and Wu, 2019). Soil biodiversity is closely correlated with soil quality and crop growth (Wang Y. et al., 2024). Long-term no-tillage practices significantly enhance soil carbon content, microbial biomass, and enzyme activity within micro-aggregates, which in turn improve soil nutrient availability and crop yield, promote soil aggregate stability, and reshape microbial community structures in semiarid agroecosystems (Han et al., 2024). Biodiverse soils exhibit greater resilience and self-repair capability, alleviating problems associated with consecutive monoculture and enhancing farm productivity (Di Sacco et al., 2021). Thus, soil biodiversity has become a key indicator for assessing soil health. By optimizing the spatiotemporal distribution of water and fertilizers, water-fertilizer coupling cultivates healthy soil biotic communities crucial for maintaining agroecosystem balance and achieving sustainable agriculture. Future research should further elucidate the mechanisms of soil biodiversity changes under water-fertilizer regulation to inform scientific farm management practices.

5.3 Soil enzyme activity

Microbial inoculants and organic fertilizers significantly enhance soil enzyme activities, notably increasing urease and alkaline phosphatase activities by up to 32.8 and 52.58%, respectively (Guangming et al., 2017). These enhancements improve soil quality and fertility in coastal saline soils by promoting more effective decomposition of organic matter and nutrient cycling. Integrating subsoiling with organic fertilizer application significantly improves soil structure, increases soil organic carbon, microbial biomass, and enzyme activities, and boosts winter wheat yield and water use efficiency by up to 32.0 and 42.7%, respectively (Yang et al., 2022b). Under deficit irrigation using brackish groundwater, combining organic manure and chemical fertilizer with an irrigation level of 150 mm (OM-I150 treatment) significantly enhances soil enzyme activities, microbial biomass, and overall soil quality. This treatment results in a 144% increase in urease activity and a 48% increase in alkaline phosphatase activity, accompanied by a notable improvement in alfalfa biomass yield over a two-year period (Jia et al., 2018). Increased nitrogen inputs and water availability in arid ecosystems significantly alter microbial enzyme activities. Specifically, the activities of β-glucosidase and phosphomonoesterase decrease by up to 47.1 and 36.3%, respectively, while N-acetyl-β-glucosaminidase activity increases by up to 80.8% (Wang et al., 2015). Crop rotations that include pulses and integrated nutrient management practices significantly enhance soil enzyme activities and microbial biomass. The activities of alkaline phosphatase, arylsulfatase, and dehydrogenase increase by 20–80%, 16–35%, and 52–79%, respectively, compared to continuous maize-wheat rotation (Borase et al., 2020). The integration of straw application with appropriate nitrogen and phosphorus supply significantly enhances soil enzyme activities, including phosphatase, β-glucosidase, protease, and urease.

The application of gypsum, manure, and rice straw significantly enhances enzymatic activities and organic matter mineralization, particularly in Solonetz soils characterized by a high sodium adsorption ratio and low electrical conductivity. This amendment results in increased CO_2 emissions, reaching levels up to 3,890 mg kg^{-1}, while simultaneously improving nutrient availability for crops (Shaaban et al., 2023). Long-term manure fertilization significantly enhances the soil's nutrient cycling capacity, as evidenced by increases in the activities of β-glucosidase, β-glucosaminidase, alkaline phosphatase, and arylsulfatase by up to 59% compared to urea-ammonium nitrate fertilization or no fertilization. These enzyme activities are strongly correlated with total carbon (C), nitrogen (N), sulfur (S), and pH, even after oven-drying and storage, underscoring the crucial role of manure in improving soil health and function (Reardon et al., 2022). These variations could be linked to dynamic changes in crop root exudates and soil moisture and temperature conditions.

A balanced water and fertilizer regimen not only increases crop yield and quality but also regulates soil biological characteristics, thereby improving soil quality (Table 2). Moderate levels of water and fertilizer inputs significantly enhance soil enzyme activities such as amylase, dehydrogenase, and phosphatase (Page et al., 2020). This enhancement promotes the decomposition of soil organic matter and contributes to maintaining the ecological balance of the soil, which is crucial for sustaining soil health and fertility in agricultural ecosystems.

During the hot and humid summer months, the activities of carbon-cycle enzymes such as amylase and invertase increase significantly, with Random Forest models achieving up to 99% accuracy in predicting these activities. In contrast, nitrogen-cycle enzymes, including urease and protease, exhibit relatively lower activity during this period (Shahare et al., 2023). This observation highlights the seasonal influence on soil biochemical processes and underscores the predictive capability of Random Forest models for enzyme activity. In winter and spring, soil enzyme activities generally decrease, with smaller fluctuations observed in phosphatase and catalase activities (Wu et al., 2020). Drought stress significantly disrupts the structure of soil microbial communities and enzyme activities, leading to reduced soil fertility and diminished plant productivity. However, these adverse effects can be mitigated through the regulation of water and fertilizers, which optimize soil environmental factors and enhance enzyme synthesis and catalysis (Bogati and Walczak, 2022).

TABLE 2 Effects of balanced water and fertilizer regimens on crop yield, quality, and soil characteristics.

Aspect	Effect	Supporting data	References
Crop yield	Increased yield with balanced water and fertilizer management.	Significant differences in yield observed between users and non-users of proper water and fertilizer practices.	Mahmoodi-Eshkaftaki and Rafiee (2020)
Crop quality	Enhanced sugar content and overall quality due to appropriate irrigation and fertilization.	Choice of irrigation water source affects crop quality and yield.	Yang et al. (2023)
Soil biological characteristics	Regulation and improvement of soil microbial community structure and activity through balanced fertilization.	Balanced fertilization enhances soil microbial biomass and diversity, promoting nutrient cycling and soil fertility.	Araujo et al. (2023)
Soil chemical properties	Improvement of soil chemical properties via balanced irrigation, aiding in nutrient availability and uptake by crop.	Proper irrigation improves soil nutrient balance, contributing to better technical quality and yield of crop.	Shen et al. (2024)
Soil physical properties	Enhanced soil aeration and water retention capacity through proper water management, supporting root growth and soil structure.	Improved root development due to better soil physical conditions resulting from appropriate irrigation practices.	Kang et al. (2022)
Nitrogen fertilizer application	Direct impact on crop growth and sugar content; requires careful management to prevent environmental degradation.	Excessive or improper use leads to soil quality degradation and water pollution; appropriate use must consider specific soil types.	Wang et al. (2023)
Irrigation system	Ensures adequate water supply at different growth stages, crucial for promoting crop growth and development.	Crop requires substantial water; proper irrigation systems are essential for optimal growth.	Kaur et al. (2024)
Irrigation water source	Choice between reclaimed water and surface water significantly affects crop growth quality and yield.	Studies indicate that different water sources alter soil properties and, consequently, crop yield and quality.	Feng et al. (2020)
Environmental impact	Improper or excessive fertilizer use can lead to soil degradation and water pollution, negatively impacting the environment.	Scientific and reasonable fertilizer application is necessary to avoid negative environmental consequences.	Azad et al. (2018)
Soil type considerations	Fertilizer application must be tailored to specific soil conditions (e.g., sandy or irrigated soils) to achieve optimal crop growth outcomes.	Appropriate nitrogen fertilizer use is closely related to soil type and requires adjustment based on soil characteristics.	Ordóñez et al. (2021)

6 Water and fertilizer optimization and environmental benefit assessment

6.1 Water-fertilizer coupling optimization strategy

The coordinated management of irrigation and fertilization not only enhances crop yield and quality but also improves the soil environment (Xu et al., 2022). The W2F4 (0.75 field capacity; rooting stage: seedling stage: flowering stage: fruiting stage = 10%: 40%: 20%: 30%) treatment, which employed irrigation at 0.75 field capacity and a fertilizer allocation of 10–40% to 20–30%, significantly enhanced the soil microbial activity of Panax notoginseng. This treatment resulted in increases of total nitrogen by 25%, organic carbon by 29.95%, and bacterial diversity indices, with Chao1 increasing by 9.33% and Shannon by 2.1%, in comparison to non-irrigated, non-fertilized controls (Shen et al., 2024). These findings highlight the potential of tailored water-fertilizer strategies to enhance soil fertility and promote microecological balance. Additionally, integrated water and fertilizer technologies reduce fertilizer loss and lower the risks of groundwater and soil pollution, supporting the sustainable development of the agricultural environment (Sang et al., 2023). However, excessive irrigation and fertilization can lead to nutrient leaching and non-point source pollution, necessitating enhanced real-time monitoring and dynamic management (Wang L. et al., 2022).

Water and nutrient requirements vary across different crop growth stages. Therefore, optimizing irrigation and fertilization timing should align with the crop growth cycle. Long-term field trials and data analyses can identify water and nutrient demand patterns during key growth stages. Subsequently, crop growth models can simulate the impacts of various irrigation and fertilization schemes on crop development and yield, facilitating the selection of optimal timing plans (Behera and Panda, 2009). Modern information technologies, such as the Internet of Things and big data analysis, are employed to establish intelligent decision systems for precise water and fertilizer management.

The primary objective of optimizing irrigation and fertilization timing is to maximize the efficiency of soil water and nutrient use. This optimization considers factors such as crop water and nutrient needs, soil physical and chemical properties, and irrigation and drainage conditions. Proper scheduling in accordance with crop growth rhythms significantly improves water and fertilizer use efficiency (Grzebisz et al., 2022). Studies indicate that moderate increases in irrigation and fertilization during critical growth stages, such as stem elongation and grain filling, can enhance crop development, yield, and quality (Hlaváčová et al., 2018). Additionally, optimizing timing not only boosts efficiency but also enhances soil environmental quality (Shah and Wu, 2019). Effective management maintains a dynamic balance of soil moisture and nutrients, promotes soil aggregate formation, and improves soil structure (Karami et al., 2012). Controlling irrigation and fertilizer applications reduces nutrient runoff and pollution, thereby decreasing non-point source pollution risks (Xia et al., 2020). Furthermore, it regulates soil temperature and moisture, creating favorable conditions for crop growth and enhancing resilience and yield stability (Jacobsen et al., 2012). Thus, optimizing irrigation and fertilization timing is essential for the efficient and sustainable use of agricultural water and nutrient resources.

Agricultural environment monitoring and early warning systems are crucial for precise integrated water and fertilizer management. By deploying various sensors in the field to collect real-time data on soil moisture, nutrients, temperature, and other environmental parameters, and integrating this with meteorological data and crop growth monitoring, a digital model of the farm environment is constructed. Model-based analyses can promptly detect anomalies in seedling conditions, pest and disease outbreaks, and soil degradation (Attri et al., 2023). Intelligent decision systems then provide optimized irrigation and fertilization recommendations for precision management (Gallardo et al., 2020). Monitoring data is essential for calibrating and optimizing water-fertilizer coupling models, which are integral to integrated farm management systems. Various coupling models have been developed for different crops and environmental conditions, such as the Jensen model for wheat and the DSSAT model for maize (Gavasso-Rita et al., 2024). These models quantify the relationship between crop development and water-fertilizer conditions, providing a scientific foundation for precise management plans. However, due to the complexity and regional variability of agricultural ecosystems, existing models encounter practical limitations, including calibration challenges and restricted applicability. This highlights the necessity for long-term field trials and comparative model research to improve their applicability and functionality (Figure 5).

6.2 Environmental benefit assessment

Through judicious and scientific irrigation and fertilization management, water-fertilizer coupling technology has been demonstrated to significantly enhance the efficiency of water and nutrient use in farmlands, thereby achieving the goal of water-saving and yield-increasing (Feng et al., 2020). Studies indicate that the implementation of drip irrigation fertilization techniques in warm winter greenhouses has a notable effect on saving water and fertilizers in the production of cucumbers (Yao et al., 2019). Appropriate irrigation and fertilization can enhance soil microbial biomass carbon and nitrogen, as well as enzyme activity, thereby ameliorating the soil micro-ecological environment (Zhang M. et al., 2022). Through the optimized irrigation and fertilization regime of water-fertilizer coupling, the efficient use of water and nutrient resources is achieved alongside the protection of the farmland ecological environment, while also realizing cost savings and increased effectiveness. Future endeavors should focus on the research of intelligent control and precision management techniques of water-fertilizer coupling, tailoring water-nutrient rates for different crops and cultivation patterns, thus promoting high-quality agricultural development and providing scientific support for national food security and rural revitalization.

Water-fertilizer coupling technology, by optimizing irrigation and fertilization management, can significantly improve the quality of the soil environment. An appropriate water and nutrient rate effectively mitigate soil salinization issues (Singh, 2021). Rational water and fertilizer management maintains the soil water-salt balance, reducing salt accumulation in the soil profile, thereby lowering the risk of soil salinization (Jia et al., 2023). Moreover, integrated water and fertilizer technology enhances soil organic matter content (Yang et al., 2020). Under the optimal water and nutrient rate treatment, the content of soil microbial biomass carbon and nitrogen increases significantly (Jia et al., 2020). Soil organic matter is a key factor in maintaining soil fertility and health, with increases in its content beneficial for improving soil physical and biological properties. A proper water and nutrient rate can optimize soil porosity and promote the formation of soil aggregates (Zhang Y. et al., 2021). A healthy soil structure is conducive to root growth and development, enhancing crop absorption and utilization efficiency of water and nutrients (Khalil et al., 2015). Additionally, rational water and fertilizer management improves soil moisture and temperature conditions, creating a favorable soil environment for crop growth. Suitable water and nutrient rates significantly increase soil enzyme activity, particularly hydrolase and urease activities. Soil enzymes are important indicators for evaluating soil quality and health. The improvement of soil enzyme activity reflected the improvement of soil biological characteristics (Bowles et al., 2014). Furthermore, reasonable water and fertilizer management helps maintain the stability of the soil microbial community structure, promoting the balance of the soil ecosystem.

6.3 Water-fertilizer coupling and application prospect

The dissemination of water-fertilizer coupling technology necessitates systematic planning and comprehensive training to enhance farmers' acceptance and application capabilities. Initially, a detailed extension pathway should be developed, outlining targets and measures for each phase. This approach should focus on demonstration areas before gradually expanding to broader regions. Strengthening training for agricultural technicians and large-scale growers is essential to enhance their roles in guidance and

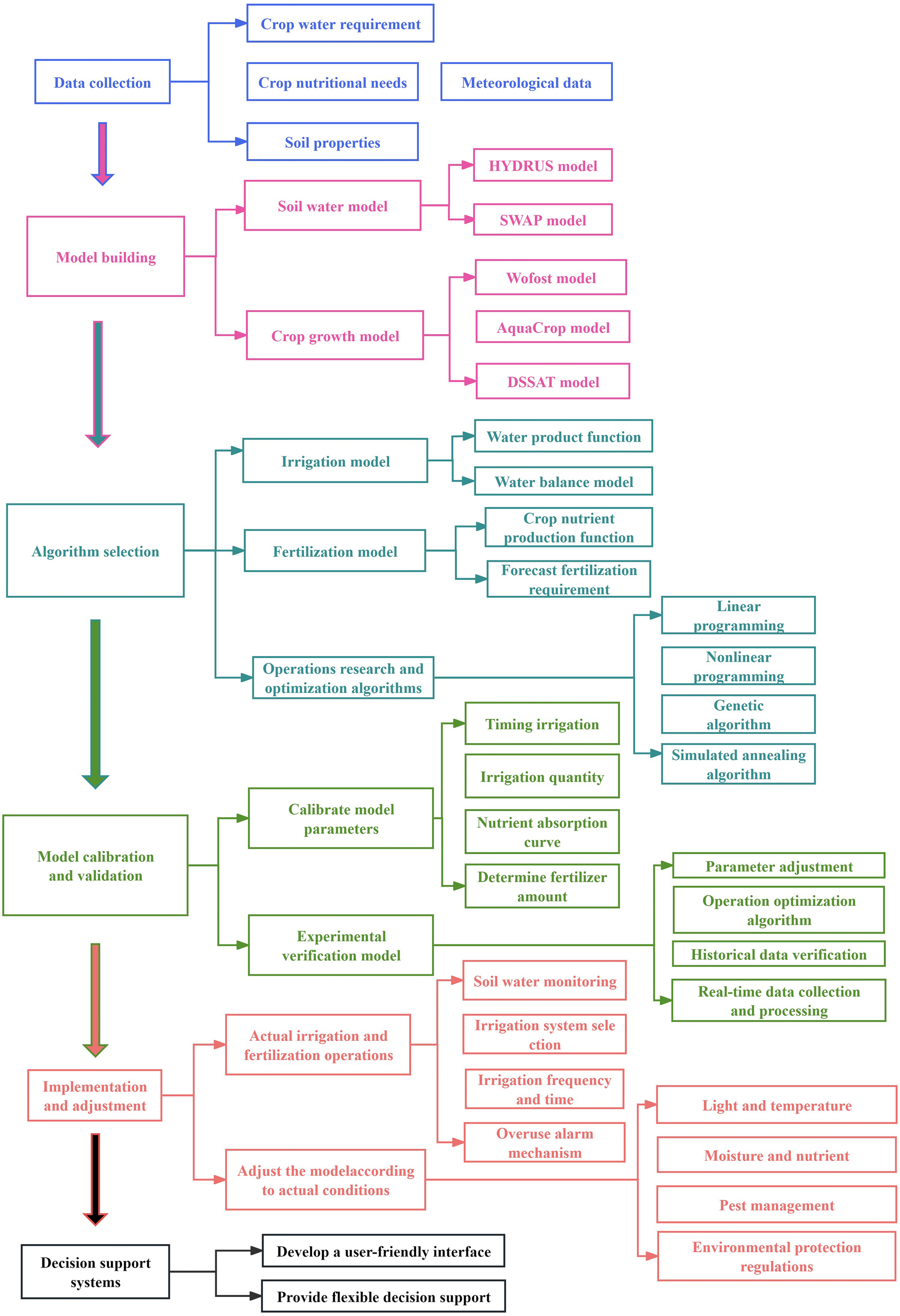

FIGURE 5
Timing optimization model for irrigation and fertilization.

demonstration, thereby enabling ordinary farmers to master the operational and management aspects of water-fertilizer coupling (Shen et al., 2013).

Simultaneously, establishing a robust technical service system is crucial for providing timely and effective support and consultation to address challenges encountered during promotion. Conducting systematic trials and demonstrations across diverse regions and crop types is essential. By creating demonstration zones that highlight the productivity and cost-saving benefits of the technology, farmers' awareness and acceptance can be enhanced. These zones should also promote adoption among neighboring farmers through field visits and technical training, thereby facilitating widespread application. The sustainable development of demonstration zones must take into account economic, social, and ecological factors to ensure long-term stability.

To address the realities of agricultural production, it is essential to implement diverse training activities that enhance farmers' understanding and application of water-fertilizer coupling technology. The utilization of modern information technologies, such as online courses and video tutorials, offers farmers convenient and practical training resources. Furthermore, organizing on-site training and observation sessions allows farmers to deepen their understanding through hands-on practice and interactive exchanges. Tailoring training content to regional and seasonal agricultural characteristics significantly enhances training effectiveness. Additionally, follow-up services and ongoing guidance are crucial for helping farmers overcome challenges in applying the technology. When promoting water-fertilizer coupling technology, it is important to consider the specific needs and conditions of smallholder farmers to increase the technology's applicability and operability. Optimizing technical schemes for smallholders, who often face limited scale and investment capacity, involves minimizing equipment and financial inputs to enhance economic viability. Providing precise support, including credit and insurance services, can mitigate application risks and foster enthusiasm (Amarnath et al., 2023). Effective communication with smallholders is key to understanding their needs and refining technical approaches, thereby improving the specificity and effectiveness of the promotion.

Support and guidance from relevant policies and regulations are essential for the effective implementation of water-fertilizer coupling technology. Government policies should prioritize water-saving agriculture by investing in agricultural water infrastructure and improving water resource efficiency (Nouri et al., 2023). Furthermore, updating agricultural resource management regulations and establishing specific ordinances for integrated water and fertilizer technologies will create legal standards for the management of these resources in agricultural production. Sustainable soil management is vital for both agricultural productivity and ecological preservation. Governments should legislate to define legal protections for soil environments, enhance soil quality monitoring and assessment, control agricultural non-point source pollution, and promote improvements in soil physicochemical and biological properties. Additionally, encouraging protective cultivation practices to mitigate soil erosion and degradation is crucial for enhancing soil fertility and farmland productivity. Achieving these goals necessitates close collaboration among agriculture, environmental protection, water conservancy, and other relevant departments to advance legislation and its implementation.

Economic measures are essential for fostering sustainable agricultural development. Governments should refine subsidy policies for water-saving irrigation and soil testing, along with formulated fertilization, to guide farmers toward the rational use of water and fertilizers. Implementing tax incentives for farmers who adopt integrated water and fertilizer technologies can encourage cost-saving and environmentally friendly practices. Strengthening agricultural science and technology extension services, in conjunction with conducting comprehensive farmer training, will enhance their understanding and application of advanced technologies. In summary, through effective policy, regulation, and economic incentives, governments can create a supportive environment for promoting water-fertilizer coupling technology. Establishing laws for water-saving agriculture and sustainable soil management, refining agricultural subsidies and tax incentives, and enhancing technical extension and training are crucial. A coordinated effort among the government, the market, and farmers is necessary to achieve the large-scale application of water-fertilizer coupling technology and promote green agricultural development.

7 Summary and prospect

This review investigates the effects of water-fertilizer coupling technology on agricultural production and its impact on the soil environment. By optimizing the supply of water and nutrients, water-fertilizer coupling better meets crop growth demands, enhancing farmland productivity. Appropriate water-nutrient rates significantly increase soil microbial biomass carbon and nitrogen contents, as well as soil enzyme activities. The increase in microbial biomass accelerates nutrient cycling, promotes the formation of soil aggregates, and improves soil structure. Soil enzymes, essential for nutrient transformation and cycling, play key roles in soil biochemical processes. Optimizing water-fertilizer rates stimulates soil enzyme activities, expediting the decomposition of organic matter and nutrient mineralization, thereby providing ample nutrients for crop growth. These findings indicate that water-fertilizer coupling technology significantly enhances soil fertility and soil quality.

However, excessive inputs of water and fertilizer cannot sustainably improve soil quality or crop production. High water-fertilizer rates may decrease soil enzyme activities, possibly due to ecological imbalances from nutrient overload. The impact of water-fertilizer rates on soil microbial biomass carbon and nitrogen is stage-specific, varying across different crop growth stages. Therefore, dynamically adjusting irrigation and fertilization plans based on crop water and nutrient requirements and soil nutrient status is essential to avoid the negative effects of over-application. Promoting water-fertilizer coupling technology not only optimizes resource allocation and enhances crop yield and quality but also contributes to improving soil environmental quality and maintaining farmland ecosystem health.

Future research should delve deeper into the interaction mechanisms among crops, soil, and water-fertilizer, strengthening the development of control models and decision support systems for water-fertilizer coupling. Long-term studies are needed to assess the sustainability of this technology, considering the cumulative and delayed effects on soil physicochemical properties and microbial activity. Systematic monitoring of dynamic changes in soil nutrient cycling, organic matter transformation, and aggregate structure evolution will help clarify the long-term mechanisms affecting soil quality and health, providing a scientific basis for formulating effective farmland management strategies.

The trend toward intelligent water-fertilizer management is noteworthy. Advances in technologies such as the IoT and big data analytics enable the integration of sensor monitoring and intelligent decision-making algorithms with water-fertilizer equipment, facilitating the construction of smart agricultural management platforms. By collecting real-time data on soil moisture, nutrient levels, and other parameters, and integrating them with crop growth models and environmental predictions, precise control and dynamic optimization of water and fertilizer can be achieved. This enhances resource use efficiency and elevates the level of intelligent agricultural production. Future research should strengthen multidisciplinary integration to develop intelligent water-fertilizer control systems suitable for different regions and crop types, promoting a transformation in modern agricultural practices.

Given the significant variability in soil environments, comparative experiments across a broader range of soil types and climatic conditions are necessary to analyze regional differences in the effects of water-fertilizer coupling. This will aid in adaptively optimizing management strategies, improving the precision and effectiveness of technology dissemination. The industrial application of water-fertilizer coupling technology urgently requires reinforcement. Currently, the lack of mature integrated water-fertilizer products and equipment limits large-scale promotion. Future efforts should focus on enhancing industry-academia-research cooperation to advance new water-soluble fertilizers, intelligent fertilization machinery, and overcome core technological bottlenecks. Establishing a comprehensive technical extension service system—including demonstration projects and farmer training—can improve farmers' awareness and acceptance of the technology. This will propel the sustainable development of water-saving and fertilizer-saving agriculture, contributing to environmental conservation and food security.

Author contributions

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Conflict of interest

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