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The role and research progress of water-fertilizer integration technology in improving the yield and efficiency of pepper cultivation

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Abstract. This article systematically reviews the application and research progress of integrated water and fertilizer technology in pepper production, focusing on the physiological mechanisms of this technology in improving the appearance, nutrition, flavor, and storage quality of peppers through water and fertilizer coordination and precise supply. It also analyzes its synergistic effects on increasing yield, water and fertilizer use efficiency, and economic benefits. The review reveals that current research still faces shortcomings such as insufficient analysis of physiological mechanisms and lack of standardization of technical parameters. In the future, it is necessary to strengthen mechanism exploration, promote parameter intelligence, and conduct interdisciplinary systematic research to fully leverage the potential of this technology in the green and sustainable development of the pepper industry.

Keywords: water-fertilizer integration, chili pepper, quality improvement, efficiency enhancement

1. Introduction

As a vital vegetable and cash crop in China, chili cultivation has seen steady expansion in recent years, playing a crucial role in ensuring vegetable supply, boosting farmers' income, and advancing rural revitalization. Statistics indicate that in 2023, China's chili cultivation area reached 2.178 million hectares, with a total output of 66.45 million tons [1]. The pepper industry not only meets daily culinary and seasoning needs but also plays a vital role in food processing, pharmaceuticals, cosmetics, and export trade [2]. However, under traditional extensive water and fertilizer management practices, the pepper industry has long faced dual challenges of high resource consumption and low utilization efficiency. Some farmers lack awareness of water resource efficiency, continuing to use traditional irrigation methods that exacerbate water consumption. Concurrently, accelerated urbanization in recent years has increased urban populations and construction activities, leading to rising municipal wastewater discharge. This disrupts river water bodies and poses risks of soil and water source degradation, further intensifying agricultural water scarcity [3]. Against this backdrop, developing water-fertilizer integration technology has become a critical pathway for promoting sustainable agricultural development, positioning it as the "top technology" in modern agriculture. By the end of 2024, China had promoted water-fertilizer integration technology across more than 170 million mu of farmland, primarily in arid regions such as Northwest China and western Northeast China.

Extensive domestic and international research has demonstrated the significant effectiveness of water-fertilizer integration technology in enhancing crop yields, improving quality, and increasing utilization efficiency. Compared to traditional management models, it achieves over 30% water savings per mu for crops like tomatoes and cucumbers, increases water use efficiency by 20 percentage points, reduces fertilizer use by over 20%, and cuts pesticide use by more than 50% [4, 5], while simultaneously boosting both yield and quality. Given current greenhouse vegetable cultivation practices, water-fertilizer integration technology is primarily applied to high-value economic crops like vegetables and melons [6]. However, existing research on its application in chili pepper production remains fragmented, lacking systematic analysis and in-depth explanation of the underlying mechanisms and interrelationships between quality enhancement and efficiency gains. Therefore, this review aims to systematically describe the application and research progress of water-fertilizer integration technology in chili pepper production. It focuses on analyzing the mechanisms and effects of improving chili pepper quality and utilization efficiency, objectively examining challenges encountered during its promotion, and outlining future research directions. This review provides theoretical foundations and decision-making references for optimizing water-fertilizer integration equipment and promoting the sustainable development of chili pepper production.

2. Mechanisms and current application status of water-fertilizer integration technology in enhancing pepper quality and efficiency

2.1. Principles of water-fertilizer integration technology, pepper water and fertilizer requirements, and current application status

Water-fertilizer integration technology is a modern agricultural innovation that combines irrigation and fertilization to conserve water and fertilizer. Its core principle involves dissolving soluble fertilizers in water through a pressurized system and delivering them precisely to the crop root zone via controlled pipelines. This enables simultaneous water and fertilizer supply for on-demand absorption, offering multiple advantages including water and fertilizer savings, labor reduction, and increased yields. A complete water-fertilizer integration system typically comprises four components: First, the headworks hub, including pumps, fertilizer tanks, and filtration systems, which handles water-fertilizer mixing, pressurization, and impurity filtration to ensure stable system operation. Second, the water distribution network, consisting of main pipes, branch pipes, and lateral pipes, responsible for conveying and distributing the water-fertilizer mixture. Third, field irrigation emitters like drip emitters and micro-sprinklers deliver water and fertilizer precisely to the crop root zone. Fourth, the control system uses sensors and controllers to intelligently regulate irrigation volume, fertilizer application rates, and irrigation timing. Common water-fertilizer integration equipment typically includes Venturi devices, pressure differential fertilizer tanks, and smart water-fertilizer machines. These achieve precise, on-demand fertilization tailored to different crops and growth stages through quantitative mixing. This not only significantly improves fertilizer utilization, boosts yields, and enhances quality but also prevents soil and fertilizer pollution.

As a vital solanaceous vegetable and cash crop, high-yield, high-quality pepper cultivation (Capsicum spp.) exhibits high sensitivity and specific patterns in water and fertilizer requirements. Throughout its growth cycle, peppers typically progress through key stages: seedling stage, transplanting and acclimation stage, flowering and fruit set stage, peak fruiting stage, and late harvest stage. Their water and nutrient requirements are not constant but exhibit phased characteristics (as shown in Table 1): Pepper nutrient demand follows a dynamic "low-high-low" pattern throughout growth, with the peak fruiting stage representing both a critical and peak period for water and fertilizer needs. Regarding nutrient preferences, peppers are potassium- and calcium-loving crops. Nitrogen is crucial for early plant development and sustained yield; phosphorus promotes root growth and flowering; potassium directly influences fruit enlargement, coloration, vitamin C accumulation, and the synthesis of secondary metabolites like capsaicin, making it a key quality-determining element; adequate calcium supply effectively prevents blossom-end rot, enhances fruit skin toughness, and improves marketable fruit rate.

Table 1. Pepper growth stages and water-fertilizer requirements

Growth Stage	Growth Center	Key Nutrient Requirements	Primary Water and Fertilizer Management Goals
Transplanting and Acclimation Period	Root Establishment	Low-concentration nitrogen and phosphorus as the main nutrients to promote root growth	Promote root growth and shorten acclimatization time
Flowering and Fruit Set Stage	Transition from vegetative to reproductive growth	Balanced supply of nitrogen, phosphorus and potassium, supplemented with boron, calcium and other micronutrients	Balance plant growth to ensure flower bud differentiation and fruit set
Peak Fruit Development Stage	Fruit enlargement and continuous harvesting	High potassium as the main nutrient, supplemented with nitrogen and calcium to achieve comprehensive nutrient supply	Ensure fruit enlargement, quality formation and sustained fruiting capacity
Late Harvest Period	Maintain plant vigor	Topdress with quick-release fertilizer to prevent premature plant senescence	Extend the harvest period and sustain late-season yields

Currently, the application of water-fertilizer integration technology in agricultural production follows a trend of "pioneering in protected horticultural crops and expanding to field crops." In chili pepper production, this technology is primarily concentrated in protected cultivation (solar greenhouses, plastic tunnels), with "drip irrigation fertilization under plastic mulch" as the predominant application model. In open-field chili cultivation, the application of drip irrigation fertilization is gradually increasing alongside the expansion of standardized planting areas and rising demands for drought resistance and water conservation.

In summary, water-fertilizer integration technology provides precise physical tools and management concepts for achieving high-yield, high-quality peppers. However, its full effectiveness must be based on a deep understanding of the pepper's inherent water and fertilizer requirements. Currently, this technology has established a significant position in pepper cultivation, particularly in protected pepper production, laying a practical foundation for its comprehensive promotion.

2.2. Mechanisms and effects of water-fertilizer integration technology on pepper quality enhancement

By integrating irrigation and fertilization, water-fertilizer integration technology enables simultaneous supply of water and nutrients, thereby systematically regulating physiological metabolism and quality formation throughout pepper growth. Its core quality enhancement lies in optimizing internal growth processes through external nutrient and environmental inputs. By adjusting water and fertilizer supply, it improves the crop's "source-reservoir-flow" relationship, guiding the synthesis, transport, and allocation of photosynthetic products to ultimately achieve target quality.This section will elaborate on both the mechanism of action and the quality-enhancing effects.

2.2.1. Mechanism of action

Water-fertilizer integration technology directly optimizes the material foundation for quality formation by creating a stable water and nutrient environment in the root zone. It enables targeted, precise supply of key quality nutrients, directly regulates secondary metabolic pathways, and comprehensively improves the plant's physiological state. The root system is the key organ for crop water and nutrient absorption and environmental sensing. Water-fertilizer integration employs a mechanism of frequent, small-volume, uniform, and continuous supply. This maintains root zone environmental stability, avoiding the soil fluctuations caused by traditional irrigation. Simultaneously, this technology improves soil structure, creating a suitable growth environment for roots. Healthy roots efficiently acquire water and nutrients, providing a sound and stable foundation for crop photosynthesis, metabolism, and fruit quality formation.

This technology also enables the timed, quantified, and proportionate supply of nutrients according to the specific fertilizer requirements of chili peppers at different growth stages, thereby directly regulating metabolic pathways related to quality. By adjusting the ratio and timing of nitrogen, phosphorus, potassium, and micronutrient supply, it guides the plant's carbon-nitrogen metabolic flow. This promotes the accumulation of metabolites like sugars and capsaicin while inhibiting excessive protein synthesis, thereby enhancing fruit flavor and specialty qualities. Optimal water and fertilizer supply enhances leaf photosynthetic efficiency, increases carbohydrate availability, and provides precursors and energy for synthesizing substances like vitamin C and capsaicin.

2.2.2. Quality enhancement effects

The synergistic effects of the aforementioned physiological mechanisms ultimately manifest as significant improvements in multiple quality indicators of chili peppers: (1) Appearance quality: Uniform fruit shape, vibrant color, consistent size, and smooth surface; (2) Nutritional and flavor quality: Optimized levels of characteristic components such as vitamin C, soluble sugars, and capsaicin, resulting in rich flavor and high nutritional value; (3) Storage and processing quality: Increased dry matter content, compact peel structure, and enhanced storage and transport tolerance; uniform ripeness and material composition meeting processing requirements, facilitating improved processing quality.

In summary, water-fertilizer integration technology systematically regulates pepper growth and metabolic processes, achieving comprehensive quality enhancement from field to table. This technology represents not only an innovation in water and fertilizer management but also a crucial physiological regulation strategy for achieving high-quality, efficient, and standardized pepper production.

2.3. Mechanisms and effects of water-fertilizer integration technology on efficiency enhancement

2.3.1. Mechanism of action

The "efficiency enhancement" inherent in water-fertilizer integration encompasses two interrelated dimensions: yield increase and efficiency optimization. By synergistically supplying water and nutrients, this technology directly promotes plant photosynthesis, extends the lifespan of functional leaves, and accumulates sufficient biomass for high yields. Simultaneously, it optimizes yield components such as fruit set rate, individual fruit weight, and harvest batches while effectively reducing flower and fruit drop rates and malformation incidence, thereby achieving significant yield increases.

Beyond direct yield gains, the core advantage lies in systematically enhancing resource utilization efficiency. Precise control of irrigation and fertilization substantially reduces deep percolation, surface runoff, and volatilization losses of water and nutrients, significantly improving key indicators like water use efficiency and fertilizer partial productivity. In practice, this technology achieves 30%-50% water savings, 20%-40% fertilizer savings, and reduced labor intensity. From an environmental perspective, its precise nutrient management reduces leaching risks, helps mitigate nonpoint source pollution, and demonstrates the coordination between production and ecology.

2.3.2. Efficiency enhancement effects

Ultimately, the aforementioned yield increases and efficiency gains must be reflected in economic benefits. Technical investments primarily encompass equipment and operational costs, while returns stem from yield improvements, quality premiums, and savings in resources and labor. Overall economic benefits are influenced by factors such as cultivation scale, crop value, and management standards, typically yielding more pronounced results under large-scale operations, high-value crop production, and scientific management. In summary, water-fertilizer integration technology advances agricultural production toward resource-intensive, environmentally friendly, and economically sustainable development through the dual pathways of "yield increase" and "efficiency enhancement."

3. Conclusion and outlook

Based on the aforementioned research, it is clear that water-fertilizer integration technology is a key production technique for advancing green, high-quality, and efficient development in the chili pepper industry. Its core value lies in fundamentally optimizing the root zone environment and physiological processes of chili pepper growth through systematic management of water-fertilizer coupling and precise supply. Regarding "quality enhancement," this technology primarily reduces physiological disorders by stabilizing the water and nutrient environment in the root zone. It also directly drives secondary metabolic pathways related to pepper appearance, nutrition, and flavor quality through precise spatiotemporal regulation of key nutrients, thereby systematically improving fruit marketability and intrinsic quality. Regarding "efficiency enhancement," it achieves increased yields by ensuring water and nutrient supply during critical reproductive growth stages, thereby improving fruit set rates and individual fruit weight. Additionally, through highly coordinated temporal and spatial water and nutrient management, it significantly reduces resource losses, elevating water and nutrient use efficiency to 1.5–2 times that of traditional methods. This approach achieves "reduced input, increased output," delivering substantial economic and ecological benefits.

However, current research and application still exhibit notable shortcomings that constrain the full realization of the technology's potential. First, most studies focus on reporting yield and quality indicators, with insufficient in-depth analysis of the intrinsic physiological response mechanisms of peppers under different water and fertilizer regimes, limiting the establishment of precise regulation models. Second, technical parameters lack a refined, standardized system based on variety, soil, and climatic conditions, leading to blindness in promotion.Finally, systematic research on socioeconomic factors in technology dissemination remains relatively weak.

Given these gaps in current research and application, future development should deepen in the following directions: First, strengthen mechanism exploration by employing multi-omics and real-time monitoring technologies to reveal physiological and molecular response networks in peppers under varying water and fertilizer regimes, laying a theoretical foundation for precision models and intelligent decision-making. Second, promote parameter standardization and intelligence by establishing a dynamic irrigation and fertilization index system that integrates variety characteristics, soil conditions, and climatic environments, and developing adaptive decision support systems based on data and algorithms. Third, conduct interdisciplinary systems research that comprehensively considers socioeconomic factors—including smallholder farmer behavior, investment returns, and industrial chain support—to construct scalable and sustainable technology application models. Only through the synergistic advancement of mechanism deepening, technology adaptation, and systematic promotion can the full potential of water-fertilizer integration technology be realized in enhancing pepper quality and efficiency while supporting sustainable agricultural development.

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