Advances in Water–Nitrogen Coupling Regulation for Sustainable Watermelon Production: A Review

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Abstract. Water and nitrogen are critical for crop growth, and their rational management underpins sustainable agricultural production. Mulched drip irrigation reduces soil evaporation and improves water use efficiency to promote crop productivity, yet watermelon cultivation widely suffers from irrational irrigation and excessive nitrogen fertilization. Such improper practices cause water and nitrogen waste and restrict improvements in watermelon yield and quality. Water-nitrogen coupling exerts dynamic stage-specific regulatory effects on watermelon growth, photosynthesis, dry matter accumulation, nutrient absorption and resource use efficiency; optimized water-nitrogen ratios can optimize agronomic traits, photosynthetic performance and dry matter allocation, thereby improving water and fertilizer utilization. This review systematically analyzes water-nitrogen coupling effects on soil conditions, plant growth and physiology, as well as watermelon yield and quality under mulched drip irrigation. It summarizes current research progress and existing limitations, and prospects future directions for precision agriculture-based water-nitrogen coordinated management. The findings provide theoretical support for efficient, eco-friendly and sustainable watermelon cultivation and scientific water-nitrogen regulation.

Keywords: Water-nitrogen coupling, Film-mulched drip irrigation, Watermelon quality and yield, Soil ecological environment, Sustainable agriculture

1 Introduction

Water and nitrogen constitute critical resources for agricultural systems, and their rational deployment is indispensable to achieving sustainable farming. Driven by growing worldwide water shortages and agricultural non-point-source contamination, enhancing water-nitrogen utilization efficiency has emerged as a core bottleneck for contemporary crop cultivation[1]. Northwest China falls within arid and semi-arid climatic zones, where scarce freshwater supplies coincide with strong evaporative potential. Under such circumstances, implementing effective irrigation and fertilization strategies is especially vital to maintain sustainable agricultural development[2].

Watermelon (*Citrullus lanatus*) is an economically important cash crop that is extensively planted across Northwest China. Nevertheless, conventional flood irrigation

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and overuse of nitrogen fertilizer frequently lead to compromised resource utilization efficiency, disordered soil nutrient status, nitrate leaching, and ecological deterioration. Plastic film-mulched drip irrigation has emerged as the primary cultivation mode in this region, as it efficiently suppresses soil water evaporation and supports accurate water and fertilizer delivery, thus elevating water and nitrogen use efficiencies[3]. In this system, reasonable water-nitrogen combinations can synergistically promote crop growth and nutrient uptake by regulating soil moisture and enhancing utilization efficiencies[4].

Prior research has demonstrated that rational water and nitrogen management exerts substantial regulatory effects on plant development, photosynthetic characteristics, nutrient absorption, fruit yield, and quality[5]. However, the interactive mechanisms underlying water–nitrogen coupling in watermelon production under film-mulched drip irrigation in the arid areas of Northwest China are still not fully clarified. Accordingly, determining the optimal irrigation and nitrogen application strategies is crucial for enhancing resource utilization efficiency and supporting the sustainable development of the local watermelon industry[6].

2 Effects of Water-Nitrogen Coupling on Soil Quality in Watermelon Fields

2.1 Effects on Soil Nutrient Content and Transformation

Water and nitrogen supply directly affect the availability, migration, and retention of soil nutrients [7]. Numerous studies have demonstrated that irrigation–fertilization interactions significantly regulate soil nitrogen transformation processes and inorganic nitrogen accumulation [8].For example, water availability can enhance nitrogen fertilizer dissolution and mobility, increasing soil ammonium and nitrate nitrogen contents, thereby improving short-term nitrogen availability for crops [9].

However, excessive water and nitrogen inputs may increase nitrogen losses and reduce fertilizer use efficiency[10]. High irrigation combined with excessive nitrogen application significantly increases NH_3 volatilization and N_2O emissions, thereby intensifying environmental risks[11]. Optimized water–nitrogen management strategies can effectively improve nitrogen use efficiency while mitigating environmental nitrogen losses.

2.2 Effects on Soil Biological Activity and Organic Matter

Water–nitrogen regulation significantly influences soil microbial community structure and enzyme activity by altering soil physical and chemical environments [12]. Soil urease activity and organic matter content are often used as key indicators of soil biological functioning. Studies have shown that appropriate water–nitrogen combinations significantly enhance soil enzyme activities and microbial metabolic intensity, thereby accelerating nitrogen cycling processes[13].Furthermore, ecosystem-level studies indicate that water level and nitrogen addition jointly regulate microbial diversity, co-occurrence networks, and functional stability, highlighting that water–nitrogen interaction is a key driver of soil ecological balance[14].

3 Effects of Water-Nitrogen Coupling on Watermelon Fruit Quality and Yield

3.1 Effects on Yield and Its Components

Yield is the most direct expression of water–nitrogen coupling effects. Within a reasonable range, increasing irrigation and nitrogen significantly improves watermelon yield [18].Studies in arid irrigation systems have confirmed that moderate irrigation combined with moderate nitrogen application (e.g., 200 $kg \cdot hm^{-2}$) achieves optimal yield and water use efficiency[16].

Excess irrigation or nitrogen application reduces economic efficiency and increases environmental risk[15].

3.2 Regulation of Fruit Quality Traits

Water–nitrogen coupling strongly affects fruit quality traits such as soluble solids, sugar content, and vitamin C.Moderate water deficit often enhances sugar accumulation by promoting assimilate translocation, while excessive irrigation dilutes fruit quality [18].CO_2 enrichment further modifies these responses, and interaction effects among CO_2, water, and nitrogen significantly regulate fruit quality formation[17].

4 Research hotspots and future trends

4.1 Current Research Hotspots of Water–nitrogen Coupling in Watermelon Production

Recent studies have increasingly focused on the physiological mechanisms underlying water–nitrogen coupling, including photosynthetic regulation, carbon–nitrogen metabolism, and stress adaptation. Hong et al. demonstrated that water–nitrogen interactions significantly regulated watermelon photosynthesis and yield formation under elevated CO_2 conditions [16].

The influence of water–nitrogen management has gradually expanded from plant responses to soil ecological processes. Water availability regulates nitrogen transformation, migration, and retention by altering soil moisture conditions, oxygen availability, microbial activity, and enzyme-mediated nitrogen cycling processes [19, 20]. Recent studies have emphasized that integrating soil physicochemical properties and microbial functional characteristics is essential for understanding rhizosphere nutrient regulation mechanisms and improving nitrogen-use efficiency in sustainable agricultural systems [21, 22].

With the development of precision agriculture, sensor monitoring, remote sensing, and artificial intelligence technologies have provided new approaches for dynamic water–nitrogen regulation. Integrating environmental information, crop growth parameters, and predictive models can improve irrigation and fertilization decisions, promoting more precise and sustainable watermelon production systems [23].

4.2 Limitations of Current Research

Existing studies are mainly conducted under specific soil, climatic, and cultivation conditions, resulting in considerable differences in optimal irrigation and nitrogen application rates among regions. Besides, most water–nitrogen management strategies are still based on traditional field experiments, and the application of real-time monitoring and intelligent decision-making technologies requires further development. The integration of Internet of Things (IoT), wireless sensors, and machine learning models provides new opportunities for real-time monitoring of soil–crop water status and dynamic optimization of irrigation management [24].

4.3 Future Perspectives and Intelligent Management Strategies

Future research should focus on establishing an integrated water–nitrogen regulation framework that connects soil processes, plant responses, and environmental factors. For instance, integrating crop growth models (e.g., DSSAT and AquaCrop), machine learning algorithms (e.g., random forest and deep neural networks), and multi-source data assimilation approaches could provide more accurate predictions of crop water and nitrogen requirements under different environmental conditions[25, 26].

Meanwhile, precision agriculture technologies, including soil sensors, remote sensing, and artificial intelligence models, should be incorporated into water–fertilizer management systems. For example, intelligent decision-support models based on real-time soil moisture monitoring, UAV-derived vegetation indices, and AI-based prediction algorithms can dynamically optimize irrigation and nitrogen application schedules according to crop growth stages and environmental variability[25]. These approaches can enable real-time adjustment of irrigation and nitrogen supply according to crop demand and environmental conditions, thereby improving resource-use efficiency and promoting sustainable watermelon production [27].

5 Conclusion

Although numerous studies have demonstrated positive effects of water–nitrogen coupling, the optimal irrigation and fertilization thresholds vary considerably among regions, soil types, and cultivars. Future studies should focus on establishing generalized decision-support models integrating soil characteristics, climate variability, and real-time sensing technologies. Moreover, molecular mechanisms underlying water–nitrogen interactions remain insufficiently understood, particularly regarding root–microbe interactions and nitrogen signaling pathways.

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Disclosure of Interests

The authors have no competing interests to declare that are relevant to the content of this article.

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