A Precision Management Framework for Water-Nitrogen in Watermelon

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Abstract. While substantial research has been conducted on irrigation and fertilization technologies for watermelon, there is still no systematic framework that integrates stage-specific water and nitrogen demand, water-nitrogen interactions, and full-growth-cycle operational rules. Most existing studies only carry out multi-factor analyses and have not yet established a unified decision-making logic. To address this research gap, this paper summarizes watermelon's stage-specific water and nitrogen demand characteristics and their physiological basis; compares the principles and applicability of response surface methodology, TOPSIS, and crop models (DSSAT, APSIM) for quantifying water–nitrogen coupling effects; analyzes how such coupling regulates plant physiological traits; and reviews advances in related regulatory measures. Based on this, we propose a precision management framework that uses stage-specific demand as the diagnostic benchmark, quantified coupling effects as the evaluation criterion for management schemes, physiological regulatory mechanisms as the scientific foundation, and regulatory technologies as the implementation pathway. Developed from watermelon's physiological needs across growth stages, this framework provides a theoretical basis for precision water and nitrogen management.

Keywords: Watermelon, Water-nitrogen coupling, Precision management framework.

1 Introduction

China is the world's largest watermelon producer and consumer, with an annual output of approximately 60 million tons, accounting for about 60% of the world's total production, and per capita consumption 3.39 times the global average [1,2]. If not properly managed, such a large-scale production system will bring considerable environmental risks. Watermelon has a shallow root system and is highly sensitive to water and nitrogen supply: insufficient water limits plant growth and fruit setting, while excessive nitrogen application impairs fruit quality [3,4]. However, China's watermelon cultivation still relies on excessive water and fertilizer, contrary to the national strategy of "reducing fertilizer use while enhancing efficiency." [1]

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Research on water–nitrogen interactions in watermelon has shifted from yield-based assessments to underlying physiological mechanisms [5]. Internationally, DSSAT and APSIM are widely used for maize and wheat and provide mature frameworks for intelligent agriculture [6,7]. In China, studies have expanded from morphology to photosynthesis and root architecture [8-10], while fertigation, mulching, and intelligent sensing have been validated across multiple crops [11,12]. Yet most watermelon research still addresses single factors or stresses [5,11] and lacks integrated, whole-growth-cycle analysis of water and nitrogen demand [12], hindering field application. Recent advances in IoT sensors, UAV remote sensing, machine learning and crop modeling now enable real-time monitoring of soil crop water and nitrogen status, delivering direct, efficient, and cost-effective on-site data that surpass traditional methods and open new pathways to overcome current limitations [13].

This review on watermelon integrates stage-specific water–nitrogen requirements, coupling analyses, physiological mechanisms, and technologies to establish a precision management framework that determines the timing, rate, and method of water and nitrogen application at each growth stage using quantitative data, not empirical rules. To ensure methodological rigor, we systematically searched Web of Science, Scopus, and CNKI for watermelon water–nitrogen management studies published from 2000 to 2026 using the keywords “watermelon”, “water–nitrogen coupling”, and “Regulation Technologies”. After deduplication, we screened records by title, abstract, and full text, prioritizing field experiments, validated models, and mechanistic studies. We excluded greenhouse- or hydroponic-only studies and those lacking extractable quantitative data.

2 Stage-Specific Water and Nitrogen Demand Dynamics

Watermelon has shallow roots and low nutrient uptake efficiency; its responses to water and nitrogen vary markedly across growth stages. Its life cycle includes five sequential phenological stages: seedling, vine elongation, flowering fruit set, fruit expansion, and maturity each duration varying by cultivar and management [3,5]. During the seedling stage, aboveground growth is minimal, so water demand is low, but root elongation is vigorous; excessive nitrogen promotes vegetative overgrowth and salt stress [14]. In the vine elongation stage, demand for both water and nitrogen rises sharply [5,13]. Nitrogen uptake peaks from vine elongation through early fruit set not during fruit expansion, and the recommended SPAD range is 60.3–63.6 [15]. At flowering and fruit set, stable water supply and moderate nitrogen are critical to avoid pollination failure and excessive vegetative growth; this stage has the second-highest water sensitivity (0.25–0.30), exceeded only by fruit expansion [16]. Fruit expansion demands the most water; rapid growth here directly determines final yield [5], but nitrogen uptake does not peak then. Excessive late-expansion nitrogen delays maturity and lowers sugar content. The optimal SPAD range for functional leaves is 64.8–66.5 [15], and water sensitivity peaks at 0.33–0.40 [16]. At maturity, both water and nitrogen demand decline. Moderate water stress promotes sugar accumulation depending on intensity and duration [14], while water sensitivity is low (0.10–0.15) [16].

3 Water-Nitrogen Coupling Effect

3.1 Basic Principles

The water–nitrogen coupling effect refers to their integrated interaction in cropping systems [17]. Water governs nitrogen availability via dissolution, transport, and root uptake, while also regulating microbial activity and organic N mineralization [3]. Conversely, nitrogen influences crop transpiration and photosynthesis by modulating leaf chlorophyll content [4]. This coupling manifests in multi-dimensions: the W × N interaction term quantifies statistical deviation from additive effects [17]; physiological synergy or antagonism is assessed by comparing crop responses under combined versus individual applications; water use efficiency (WUE) and nitrogen use efficiency (NUE) often diverge, necessitating independent analysis [5,10].

3.2 Quantification Models

Three core methodological approaches study water–nitrogen coupling: statistical regression, comprehensive evaluation, and crop growth models. Among these, statistical regression, particularly response surface methodology (RSM), constructs quadratic equations linking yield (Y) to irrigation (W) and nitrogen (N) application (Eq. 1) [18]. These models quantify main and interaction effects via regression coefficients and identify theoretical optimal W–N combinations. However, while RSM detects non-additive combined effects, it cannot determine their direction (positive or negative) or underlying mechanisms [19]. Moreover, the global optimum must be translated into stage-specific irrigation and fertilization schedules using root-zone water balance and crop nitrogen demand [5,16].

$$Y = a_0+a_1W+a_2N+a_3W_2+a_4N_2+a_5W\times N \quad (1)$$

where Y is crop yield (kg/hm²); W, irrigation amount (m³/hm² or mm); N, nitrogen rate (kg/hm²); a_0, intercept; a_1 and a_2, linear coefficients; a_3 and a_4, quadratic coefficients; a_5, interaction coefficient for water–nitrogen coupling [18].

Comprehensive evaluation models like TOPSIS integrate yield with multiple factors, such as crop growth, fruit quality, and resource use efficiency [20,21]. Yet TOPSIS only ranks predefined treatments; it cannot detect water–nitrogen synergies or antagonisms, nor predict the performance of untested combinations. Moreover, overlapping indicators (e.g., yield and water use efficiency) may confound evaluation [20]. In contrast, process-based models (e.g., DSSAT, APSIM) mechanistically simulate soil–plant–atmosphere interactions jointly modeling water and nitrogen balances, dynamic transport, and crop growth to provide mechanistic insight and temporal predictions [21,22]. However, they were developed for upright crops (e.g., maize, wheat); their assumptions on canopy interception, dry matter partitioning, and root water uptake poorly reflect climbing watermelon physiology [22]. Though species-specific calibration can extend them to watermelon, dedicated parameter sets remain scarce, and reliable simulation still depends on sufficient field data [21].

4 Effects of Water-Nitrogen Coupling on Watermelon

The synergistic effect of water and nitrogen is clearly reflected in watermelon physiology. Optimal supply of both maximizes plant height; conversely, moderate nitrogen can mitigate water stress [3]. Root morphology depends on the nitrogen form; nitrate generally outperforms ammonium [8]. At the cellular level, the ClACO gene regulates nitrogen uptake by modulating ethylene release and shaping root architecture [23]. Photosynthesis closely interacts with water–nitrogen supply to govern yield and quality: water deficit or imbalance reduces stomatal conductance, Rubisco activity, and PSII efficiency; moderate supply (65% field capacity, 200 kg N/ha) boosts antioxidant enzymes (CAT, POD) and GS/NR activity, enhancing carbon assimilation [24]. Though yield and quality are key metrics, their optimal water–nitrogen regimes differ: high yield requires ample water and nitrogen, whereas high quality benefits from mild water deficit and lower nitrogen [3] Thus, effective water–nitrogen management in watermelon requires balancing yield and quality, not maximizing either alone.

5 Regulation Technologies

Current regulatory techniques fall into three categories: integrated water-fertilizer management, mulching and soil improvement, and smart sensing and decision-making [8,11]. Water-fertilizer integration delivers water and nitrogen synchronously to the root zone via irrigation, enhancing water use efficiency and fruit soluble solids content in watermelon with minimal yield loss, under physiological synergy of water and nitrogen [5]. Mulching and soil amendments enhance root-zone water and nutrient retention, reducing losses from evaporation, leaching, and drainage [10]. Plastic film mulching curbs soil evaporation and raises soil temperature; straw mulching improves water infiltration and soil water storage [9]. While soil conditioners improve aggregate stability to reduce runoff and nutrient loss [25]. Combined with integrated water–fertilizer management, these practices jointly minimize water and nitrogen waste. Intelligent sensing and decision-making enable data-driven water and nitrogen management through a closed-loop workflow of sensing, diagnosis, decision-making, and execution [11]. Multispectral, thermal, soil moisture, and sap flow sensors monitor canopy growth and root-zone conditions [13]; dynamic thresholds trigger irrigation events; and LoRa or NB-IoT protocols forward commands to actuators [12]. Zhu et al. [13] estimated leaf water content using UAV multispectral data, while Adamo et al. [12] integrated sensing, cloud storage, and decision outputs into a full-chain framework.

6 Conclusion

In summary, while previous studies have extensively examined isolated water and nitrogen factors in watermelon, the original contribution of this work lies in constructing a unified closed-loop precision management framework that integrates stage-specific

demand diagnosis, coupling-effect quantification, physiological regulation, and technological implementation into a cohesive decision-making logic. This framework shifts water-nitrogen management from static, empirical recommendations to a dynamic, physiology-driven paradigm, providing a theoretical reference for achieving synergistic improvements in yield, quality, and resource efficiency. However, practical challenges still exist, including ambiguous diagnostic criteria, non-universal quantification standards, and unverified technical synergy. Accordingly, future research should focus on establishing quantitative supply-response relationships, incorporating demand thresholds into decision-making models, and validating this framework under diverse field conditions to bridge the gap between theoretical research and practical application.

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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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