Research Progress on Water-Fertilizer Coupling Regulation Mechanism and Efficient Cultivation of Facility Watermelon in Arid Regions

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Abstract. Facility-grown watermelon production in arid areas has advantages such as abundant solar and thermal resources, high yield potential, and prominent commercial value. This article reviews the mechanisms of water and fertilizer coupling in arid area facility-grown watermelons on root zone water and salt transport, root system absorption, yield formation, and fruit quality. It summarizes the research progress of deficit irrigation, subsurface drip irrigation, alternate root zone irrigation, and intelligent water and fertilizer integration technologies. Based on this, an efficient cultivation path is proposed, which is based on the nutrient absorption patterns during the growth period and takes into account yield, quality, resource efficiency, and environmental effects. In the future, more regional long-term experiments and digital decision-making model research should be strengthened to provide theoretical basis for precise water and fertilizer saving and green production of facility-grown watermelons in arid areas.

Keywords: Facility agriculture; Watermelon; Water and fertilizer integration; Water use efficiency; Arid area

1 Introduction

Watermelon is a horticultural crop with high water demand, whose yield and quality are highly sensitive to the timing of water supply. In arid regions, where air is dry and diurnal temperature fluctuations are large, high temperatures and high vapor pressure deficits inside greenhouses may intensify canopy transpiration. Long-term plastic mulching, drip irrigation, and intensive fertilization can easily lead to localized wet zones, salt accumulation at soil edges, and residual nitrate nitrogen in the soil. Insufficient irrigation restricts root water uptake, nutrient transport, and leaf photosynthesis, while excessive irrigation may cause oxygen deficiency in the root zone, deep percolation, and nutrient loss. Inadequate fertilization fails to support fruit expansion, whereas over-fertilization promotes excessive vegetative growth, reduces nitrogen use efficiency, and degrades fruit quality[1]. Therefore, the goal of protected watermelon pro-

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duction should shift from merely pursuing high yields to achieving coordinated improvements in yield, quality, resource efficiency, economic returns, and environmental safety.

2 The Mechanism of Water and Fertilizer Coupling Regulation

2.1 The Synergistic Effect of Water and Nutrient Migration in the Root Zone

Water serves as the medium for nutrient migration to root surfaces. Optimal soil moisture content maintains high root hydraulic conductivity, promotes nitrate movement via mass flow, and enhances the diffusion rates of phosphorus, potassium, and other elements in the rhizosphere. However, overly frequent irrigation or excessively high fertilizer concentrations in a single application can lead to root concentration in surface layers, salt accumulation, and reduced crop stress tolerance. Negative pressure irrigation experiments show that applying a supply pressure of approximately -5 to -15 kPa during different growth stages can create relatively stable root zone moisture conditions; compared with furrow irrigation, this method reduces water use by 18.3% to 31.2% and increases water productivity by 36.6% to 53.8%[2].

2.2 Root system Configuration and Water and Fertilizer Absorption Capacity

Moderate water deficiency can induce the roots to grow towards deeper or wetter soil layers, increasing the root-to-shoot ratio and the absorption capacity per unit root length. Appropriate nitrogen fertilizer can increase the length of fine roots, the root surface area and the number of root tips, but excessive nitrogen application often promotes rapid growth of the above-ground part, reducing the root-to-shoot ratio and intensifying the transpiration demand of the canopy. Only when water and fertilizer supply are synchronized with the growth rhythm of the roots can the increased root absorption capacity be transformed into dry matter and fruit yield[3]. The key points of water and fertilizer coupling regulation during different growth stages of the facility watermelon are shown in Table 1.

The intelligent drip irrigation and fertilization experiment showed that by adjusting the upper and lower limits of soil moisture, the depth of moisture saturation, and the nutrient input according to the growth stage, it is possible to promote the formation of absorption roots, and improve the root system's ability to absorb and transport water and nitrogen, phosphorus, and potassium. The fruit expansion stage is the core period for substance accumulation in watermelons, during which the dry matter accumulation accounts for approximately 79.0% of the entire growth period, and the absorption amounts of nitrogen, phosphorus, and potassium account for approximately 67.9%, 72.4%, and 71.8% respectively[4]. This indicates that the traditional method of evenly distributing fertilizers is difficult to meet the plant's needs, and the focus of topdressing should be shifted to after fruit setting and during the fruit expansion period. At the same time, excessive nitrogen application should be avoided during the maturity stage.

Table 1. Key points of water and fertilizer coupling regulation for different growth stages of facility watermelon

Growth stage	physiological process	Water regulation	Nutrient regulation
Seedling stage	Root system recovery, leaf establishment	Medium-frequency, small-scale irrigation	Low-concentration starter fertilizer.
Vegetative growth stage	Leaf area expansion and root-shoot system formation	Maintain a relatively stable water supply	Appropriate amount of nitrogen combined with phosphorus and potassium
Blossom stage	Pollination and fertilization, cell division of young fruits	Improve the timeliness of irrigation	Control the concentration of nitrogen.
Enlargement stage	The fruits rapidly gain weight and concentrate on absorbing nutrients.	Ensure adequate moisture in the root zone and the depth of soil moisture saturation	Simultaneous application of water and fertilizer
Mature stage	Sugar accumulation, acid metabolism and coloring	Mild water shortage, reduction in irrigation frequency	Reduce the use of nitrogen fertilizer and supplement with a small amount of potassium.

2.3 Production Volume Formation and Quality Regulation

The yield of watermelons is mainly determined by the fruit setting rate, the quality of individual fruits, and the proportion of marketable fruits. Insufficient water during the flowering and fruit setting period will affect pollination, fruit setting, and the cell division of young fruits; insufficient water during the fruit expansion period will directly limit the fruit size and the quality of individual fruits. The experiments in the Hexi Oasis show that water consumption during the fruit expansion period accounts for 33.15% to 40.33% of the total growth period; water deficiency during the vine extension period and the fruit expansion period is likely to inhibit stem and leaf growth, while mild water deficiency during the ripening period performs better in the comprehensive evaluation of yield, quality and water use efficiency[5].

3 Research Progress on Efficient Coupling and Regulation Technology of Water and Fertilizer

3.1 Subsurface Drip Irrigation and Staged Water Deficit Management

Sub-surface drip irrigation has become the main form of water and fertilizer integration in greenhouse watermelon cultivation in arid areas by reducing soil surface evaporation, limiting non-root zone moisture, and improving fertilizer placement accuracy. Different water and fertilizer combination experiments have shown that moderate irrigation combined with appropriate fertilization usually can balance plant growth, photosynthetic

capacity, yield, quality, and irrigation water use efficiency, while high water and high fertilizer do not necessarily achieve the highest overall benefit. Research in the Guanzhong region adopts a comprehensive evaluation of yield, quality, and water and fertilizer use efficiency, and proposes that under the condition of abundant water and fertilizer resources in the local area, an optimized allocation can be made according to approximately 0.73 times the transpiration water requirement and 1.03 times the target yield fertilizer level[6].

3.2 Alternate Root Zone Drip Irrigation Fertilization

The Comparative assessment of major water-saving irrigation strategies are shown in Table 2. Alternate root zone drip irrigation alternates between moistening the root zone and drying it, allowing the moist side to maintain water and nutrient absorption while the dry side generates chemical signals to regulate the opening of stomata, thereby reducing water loss through transpiration. Relevant studies have shown that compared with conventional drip irrigation under the same water and nutrient levels, this technology can promote root and above-ground growth, increase photosynthetic rate and absorption of nitrogen, phosphorus, and potassium. Under specific experimental conditions, a 40% reduction in water and nutrient input did not cause a decrease in yield. The irrigation water use efficiency was 67.8% to 78.7% higher than that of conventional drip irrigation with sufficient water and nutrient input, and the soluble solids, vitamin C, and sugar-acid ratio of the fruits were also improved[7,8].

Table 2. Comparative assessment of major water-saving irrigation strategies

Irrigation strategy	Core principle and technical characteristics	Major advantages	Main limitations and potential risks	Most suitable application scenarios
Subsurface- deficit irrigation	Controlled degree of soil-water deficit during selected growth stages.	Restrict excessive vegetative growth and promote assimilate partitioning toward reproductive organs	The effect is highly dependent on the type of crop, variety, growth stage, soil texture and climatic conditions.	Drought-tolerant field crops; farms with limited water allocations but adequate capacity for soil-moisture or evapotranspiration-based scheduling.
Partial root-zone drying	Approximately half of the root system is irrigated while the other half is allowed to dry	Limits excessive shoot growth and improves canopy microclimate	Responses vary greatly among crop species, cultivars, rootstocks, soil types, and environmental conditions	Arid and semi-arid regions; allow distinct wet and dry root-zone compartments to be maintained
Smart integrated water-fertilizer management	Irrigation and nutrient delivery are jointly regulated using sensor networks, automated control systems, decision-support models	Improves water productivity, fertilizer-use efficiency, and nutrient recovery; reduces nutrient leaching, runoff	High capital costs for sensors, controllers, communication infrastructure, injectors, and software platforms; technical complexity may limit adoption by smallholders	Greenhouses, controlled-environment agriculture, high-value horticultural crops, intensive orchards, seed production, and large-scale precision farming

4 Challenges and Prospects

(1) The lack of universality in regional parameters

The current studies mostly involve single-location, few-variety and 2-3 growing-season experiments. Different studies adopt inconsistent expressions for field water holding capacity, evaporation pan coefficient, irrigation lower limit and fertilization, making it difficult to directly compare the results. In the future, unified experiments should be conducted in typical regions such as Hexi Corridor, South Xinjiang, Ningxia, Northern Shaanxi and Guanzhong. A standardized database including meteorological, soil, variety, rootstock, irrigation, fertilization, yield and quality information should be established.

(2) Intelligent decision-making is still at the stage of moisture threshold control.

At present, most intelligent systems mainly rely on single-point soil moisture sensors to start and stop irrigation, and insufficiently utilize data on root zone electrical conductivity, nutrient concentration, crop transpiration, and canopy temperature. In the next stage, it is necessary to integrate facility meteorology, soil water and salt content, crop phenotyping, and historical yield data to construct a closed-loop control model of "evapotranspiration prediction - water and fertilizer demand diagnosis - equipment execution - growth feedback".

(3) The interaction between variety, rootstock and water and fertilizer management needs to be strengthened.

Different varieties of watermelons show significant differences in root structure, stomatal regulation, fruit size and sugar accumulation. Grafting the rootstock also alters water absorption capacity, mineral element absorption and drought resistance. Studies have shown that suitable rootstocks can improve water relations and yield stability under water shortage conditions, but they may also affect fruit flavor and mineral composition. In the future, the selection of drought-tolerant and salt-tolerant rootstocks should be coordinated with the design of precise water and fertilizer systems to form a variety-rootstock-water and fertilizer combination suitable for different maturity periods, fruit shapes and market targets.

5 Conclusions

The core of water and fertilizer coupling regulation for facility watermelon in arid areas lies in synchronizing the water status in the root zone, the effective concentration of nutrients, the root absorption capacity, and the strength of the fruit storage reservoir in terms of time and space. Appropriate fertilization can enhance root vitality and canopy photosynthetic capacity. Based on current research, facility watermelons are recommended to adopt sub-surface drip irrigation and divided fertilization. During the seedling stage, maintain stable low-concentration water and fertilizer supply; avoid significant water fluctuations during flowering and fruit setting; strengthen water and potassium synchronization supply during the fruit expansion period; and implement mild water restriction and strict nitrogen control during the maturity stage. Negative pressure irrigation, alternate root zone drip irrigation, and sensor feedback intelligent water and

fertilizer integration all show good potential for water and weight reduction. In the future, a production system for facility watermelon in arid areas should be established that takes into account high yield, high quality, water conservation, weight reduction, efficiency improvement, and ecological security.

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Disclosure of Interests

The authors declare no competing interests.

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