Journal of Recent Trends in Agriculture and Natural Science
Volume 2, Issue 2, Pages 9-17, 2026 (April-June)
ISSN (online): 3139-1494
DOI: https://doi.org/10.47001/JRTANS/2026.202002
Available Online at https://jrtans.com

Water-Saving Strategies for Watermelon Production: A Review of Deficit Irrigation and Mulching Effects on Yield and Water Use

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Abstract: Water scarcity is a critical constraint to agricultural productivity in arid and semi-arid regions worldwide, necessitating the adoption of water-saving strategies for high-water-demanding crops such as watermelon (Citrulluslanatus L.). This review synthesizes current scientific evidence on the yield and water use responses of watermelon to deficit irrigation and mulching practices. Research from diverse agro-ecological regions, including the Hexi Oasis in China, the Mediterranean region, and semi-arid Ethiopia, demonstrates that deficit irrigation strategies significantly influence watermelon photosynthesis, yield components, fruit quality, and irrigation water use efficiency (IWUE), with the magnitude of response depending on the timing and severity of water stress. Studies indicate that mild water deficit during the seedling stage combined with moderate deficit during the maturity stage (T2 treatment) achieved the highest IWUE of 0.78 $t \cdot ha^{-1} \cdot mm^{-1}$, representing a 10.50% increase over full irrigation, while maintaining yields comparable to well-watered controls. Evidence further reveals that mulching particularly black plastic mulch and straw mulch enhances soil moisture conservation, reduces evaporation, improves soil temperature regulation, and can compensate for the negative effects of deficit irrigation on yield. Straw mulching has been shown to conserve up to 262.75 mm of water under 50% deficit irrigation compared to non-mulched treatments. The integration of deficit irrigation with mulching emerges as a promising strategy for achieving optimal water productivity while sustaining fruit quality, with plastic mulch combined with 70% irrigation recording the highest water productivity of 15.1 $kg \cdot m^{-3}$. This review highlights that the effectiveness of combined deficit irrigation and mulching strategies depends on varietal selection, growth stage sensitivity, and local environmental conditions, emphasizing the need for site-specific recommendations to optimize watermelon production in water-limited environments.

Keywords: Watermelon, deficit irrigation, mulch, water use efficiency, yield response, fruit quality.

1. Introduction

Watermelon (*Citrulluslanatus L.*) is a sprawling annual vine belonging to the Cucurbitaceae family, valued worldwide for its thirst-quenching, nutrient-rich fruit. According to FAO statistics, the global harvest area and production of watermelon reached approximately 3.03×10^6 ha and 101.56×10^6 t, respectively. However, watermelon has high water consumption and is sensitive to changes in soil moisture, especially during its critical water demand periods, when increases or decreases in water supply can significantly affect growth, fruit yield, and quality.

Water scarcity is a major issue affecting agricultural production in arid and semi-arid regions, where agriculture consumes close to 70% of total freshwater resources. Rising global temperatures intensify drought severity, threatening agricultural water security and food production. These challenges have necessitated the development of water-saving agricultural practices to achieve rational and efficient utilization of limited water resources while promoting sustainable agricultural development.

Deficit irrigation—the practice of applying water below full crop evapotranspiration requirements at specific growth stages—has emerged as a valuable strategy for water conservation. By exploiting the crop's adaptations to water stress, deficit irrigation achieves water saving, yield stabilization, and quality regulation. However, the effectiveness of deficit irrigation depends on the timing, duration, and severity of water stress, as well as the crop's growth stage sensitivity to water deficits. Mulching—the

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application of organic or synthetic materials to the soil surface—complements deficit irrigation by reducing evaporation, conserving soil moisture, regulating soil temperature, suppressing weeds, and improving soil fertility. Common mulching materials include black plastic, straw, and organic residues, each with varying effects on soil water dynamics and crop performance.

This review synthesizes current scientific evidence on the yield and water use responses of watermelon to deficit irrigation and mulching, examining the physiological mechanisms underlying these responses and evaluating the practical implications for sustainable watermelon production in water-limited environments. The fruit contains approximately 90–92% water and is an excellent source of vitamins A and C, lycopene, antioxidants, dietary fiber, and essential minerals. Watermelon cultivation contributes significantly to the agricultural economy of many developing countries, particularly in Africa, Asia, and parts of South America, where it provides income opportunities for smallholder farmers and commercial producers. However, watermelon production requires substantial amounts of irrigation water, especially during flowering, fruit set, and fruit enlargement stages. Increasing global water scarcity, climate change, irregular rainfall patterns, and competition for freshwater resources have become major constraints affecting sustainable watermelon cultivation. Consequently, efficient irrigation management has become an important research priority aimed at maximizing crop productivity while minimizing water consumption.

Agriculture accounts for nearly 70% of global freshwater withdrawals, making water conservation an essential component of sustainable crop production systems. Traditional irrigation methods often apply water beyond crop requirements, resulting in considerable losses through evaporation, deep percolation, and surface runoff. These inefficiencies not only waste valuable water resources but also increase production costs and reduce irrigation efficiency. Therefore, researchers have focused on developing innovative water-saving technologies capable of maintaining acceptable crop yields under limited water availability. Among the various approaches investigated, deficit irrigation and mulching have emerged as practical, economically feasible, and environmentally sustainable techniques for improving water use efficiency in watermelon production.

Deficit irrigation refers to the deliberate application of irrigation water below the full crop evapotranspiration requirement during selected growth stages without causing severe reductions in yield. This strategy encourages plants to utilize available soil moisture more efficiently while reducing excessive vegetative growth and minimizing non-productive water losses. Numerous studies have demonstrated that carefully managed deficit irrigation can substantially reduce irrigation water requirements while maintaining acceptable fruit yield and improving certain quality attributes such as soluble solids, sweetness, firmness, and antioxidant content. The effectiveness of deficit irrigation depends on irrigation scheduling, crop growth stage, soil type, climatic conditions, and irrigation methods, with drip irrigation being particularly suitable for precise water application.

Mulching represents another widely adopted agronomic practice that significantly improves soil moisture conservation. Organic mulches such as straw, grass residues, compost, and crop residues, together with inorganic materials including black polyethylene film, biodegradable plastic films, reflective films, and woven mulches, reduce soil evaporation, suppress weed growth, moderate soil temperature fluctuations, and improve soil structure. By minimizing direct soil exposure to solar radiation and wind, mulching effectively conserves soil moisture, reduces irrigation frequency, and enhances crop performance under water-limited conditions. Furthermore, mulching contributes to improved microbial activity, enhanced nutrient availability, and reduced soil erosion, thereby promoting sustainable soil health and long-term agricultural productivity.

Recent research increasingly recommends integrating deficit irrigation with mulching technologies to maximize water conservation and crop productivity simultaneously. This combined approach enables farmers to optimize irrigation scheduling while maintaining favorable soil moisture conditions around the root zone. Such integrated water management strategies have shown considerable potential in reducing irrigation water use by 20–40% while maintaining marketable fruit yield and improving fruit quality. Therefore, this review critically examines recent advances in deficit irrigation and mulching practices for watermelon production, summarizes their individual and combined effects on plant growth and productivity, and identifies future research directions for sustainable watermelon cultivation under changing climatic conditions. This strategy encourages plants to utilize available soil moisture more efficiently while reducing excessive vegetative growth and minimizing non-productive water losses.

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2. Deficit Irrigation Effects on Watermelon Growth, Yield, and Quality

Deficit irrigation has become one of the most widely studied water-saving strategies in watermelon cultivation because of its ability to improve irrigation efficiency without causing substantial yield reductions. The technique involves supplying irrigation water below the crop's full evapotranspiration demand during specific developmental stages while minimizing physiological stress. Numerous field experiments have demonstrated that moderate deficit irrigation, typically supplying between 70% and 85% of crop evapotranspiration requirements, can reduce irrigation water consumption by up to 30% while maintaining more than 90% of maximum fruit yield. These findings indicate that watermelon possesses a moderate capacity to tolerate controlled water stress when irrigation scheduling is properly managed.

Water availability directly influences vegetative growth, leaf area development, vine elongation, root architecture, flowering behavior, and fruit development. Severe water deficits reduce cell expansion, photosynthetic activity, chlorophyll content, and nutrient uptake, leading to reduced biomass accumulation and fruit size. However, moderate water deficits often stimulate deeper root growth and improve root water extraction efficiency, allowing plants to utilize available soil moisture more effectively. Researchers have reported that deficit irrigation can enhance root-to-shoot ratios, enabling watermelon plants to maintain physiological activity under drought conditions.

Several studies have observed significant improvements in fruit quality under controlled deficit irrigation. Water stress during fruit maturation frequently increases soluble solids concentration (°Brix), sugar accumulation, lycopene content, vitamin C concentration, and antioxidant activity. These improvements are largely attributed to reduced water dilution within the fruit tissues and enhanced carbohydrate partitioning toward developing fruits. Consequently, deficit irrigation not only conserves irrigation water but also increases market value by producing sweeter and higher-quality fruits preferred by consumers.

2.1 Physiological Responses to Water Deficit

Water deficit significantly alters the physiological processes of watermelon plants, with the severity of response increasing with the intensity of water stress. Research conducted in the Hexi Oasis of northwest China demonstrated that water deficit significantly reduced the net photosynthetic rate (Pn), transpiration rate (Tr), and stomatal conductance (Gs) of watermelon leaves. Importantly, the reduction in Pn was smaller than that of Tr and Gs, suggesting that stomatal closure—a primary plant response to water stress—reduces water loss more than carbon assimilation, thus improving water use efficiency at the leaf level.

Figure 1: Watermelon Drip Irrigation with Recycled Bottles

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Modern irrigation scheduling technologies including soil moisture sensors, remote sensing, evapotranspiration modeling, wireless sensor networks, and automated drip irrigation systems have further improved the effectiveness of deficit irrigation. Precision irrigation systems allow real-time monitoring of soil water status and plant water requirements, enabling farmers to optimize irrigation timing and volume while minimizing unnecessary water applications. The timing of water deficit exposure critically influences the physiological response. Studies have shown that water deficit during the seedling stage and maturity stage produces different effects on photosynthesis and dry matter accumulation. The multi-stage irrigation pattern of mild water deficit at the seedling stage combined with moderate water deficit at the maturity stage (T2) emerged as a particularly effective strategy, significantly improving irrigation water use efficiency while maintaining yield.

Under severe water stress, the Crop Water Stress Index (CWSI) increases substantially, providing a quantitative measure of plant water status. Research has established that a 0.10 unit increase in CWSI decreases watermelon fruit yield by approximately 10%. Grafted watermelons onto wild watermelon rootstock have demonstrated higher CWSI thresholds (0.20) compared to ungrafted plants (0), indicating greater drought tolerance.

2.2 Yield Response and Yield Response Factor

The yield response of watermelon to deficit irrigation varies with the severity and timing of water stress. Studies from the Mediterranean region revealed that exposure of watermelon plants to severe deficit irrigation (50% of irrigation water requirements) resulted in significant reductions in dry biomass, total and marketable yield, average fruit weight, and fruit number. However, moderate deficit irrigation (75% of irrigation water requirements) often achieves yields comparable to full irrigation, particularly when water stress is applied during less sensitive growth stages.

The yield response factor (ky)—a measure of crop sensitivity to water stress—provides a quantitative basis for understanding yield-water relationships. Research on lady bell watermelon varieties demonstrated high sensitivity to water stress, with a ky value of 1.27 under non-mulched conditions with 50% water application. In contrast, plants grafted onto wild watermelon rootstock exhibited ky values less than 1.00, indicating greater drought tolerance and yield stability under water stress. The selection of appropriate rootstocks and varieties thus emerges as a key strategy for mitigating yield losses under deficit irrigation.

Findings from the Hexi Oasis study showed that the yield of the mild deficit treatment (T1) was the highest and showed no significant difference from the full irrigation control (CK), followed by the moderate deficit treatment (T2), with no significant difference between T1 and T2. This indicates that mild to moderate deficit irrigation, when properly timed, can maintain yields comparable to full irrigation while significantly saving water.

2.3 Fruit Quality Enhancement under Deficit Irrigation

Contrary to the negative effects on yield, deficit irrigation often improves watermelon fruit quality. Research has consistently demonstrated that water deficit treatments significantly increase the contents of soluble solids (SS), soluble sugar (SU), vitamin C (Vc), and soluble protein (SP) in watermelon fruits. The largest increases in quality parameters were observed in the T2 treatment (mild deficit at seedling stage combined with moderate deficit at maturity stage), suggesting that strategic water stress can enhance fruit sweetness and nutritional value.

The physiological basis for quality improvement under deficit irrigation lies in the concentration of sugars and other solutes as water availability decreases, as well as stress-induced metabolic changes that enhance the biosynthesis of secondary metabolites. However, fruit ripening has been identified as the least sensitive stage to water deficits, and severe water stress during ripening may not compromise quality as much as stress during other growth stages.

3. Mulching Effects on Soil Water Conservation and Crop Performance

Mulching has become an indispensable agronomic practice for conserving soil moisture and improving crop performance under water-limited environments. Both organic and synthetic mulches function by creating a protective barrier over the soil surface

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that reduces evaporation losses, suppresses weed growth, minimizes soil crusting, and moderates soil temperature fluctuations. The resulting improvement in soil moisture availability significantly enhances root development, nutrient uptake, microbial activity, and overall plant growth.

Plastic mulch, particularly black polyethylene mulch, has gained widespread popularity in commercial watermelon production because of its effectiveness in increasing soil temperature during early crop establishment while simultaneously reducing evaporative water losses. Studies consistently report that plastic mulching increases soil water retention by 20–35%, improves irrigation efficiency, and enhances fruit yield compared with bare soil cultivation. Reflective and silver-colored mulches additionally reduce insect infestation by disrupting pest orientation and improving light distribution within the crop canopy.

Organic mulches such as wheat straw, rice straw, maize residues, sugarcane trash, compost, wood chips, and grass clippings provide multiple agronomic and environmental benefits. Besides conserving moisture, organic mulches gradually decompose, enriching soil organic matter, improving soil aggregation, increasing microbial diversity, and enhancing nutrient cycling. Long-term application of organic mulches contributes to sustainable soil fertility while reducing dependence on synthetic fertilizers.

Mulching also reduces weed competition, thereby decreasing competition for water, nutrients, and sunlight. Weed suppression minimizes herbicide application, reduces production costs, and contributes to environmentally friendly crop production systems. Additionally, mulch protects fruits from direct soil contact, reducing fruit rot, pathogen infection, and mechanical damage while improving marketable fruit quality.

3.1 Soil Moisture Conservation and Water Saving

Mulching plays a crucial role in soil water conservation by reducing evaporation, improving infiltration, and maintaining favorable soil moisture conditions. Research has consistently demonstrated that both plastic and organic mulches enhance soil water availability compared to bare soil conditions.

Figure 2: Watermelon Mulching Film

Studies from the Loess Plateau of northwest China revealed that soil water content fluctuated more in the 0–40 cm depth interval than in the 80–120 cm depth interval, suggesting that watermelon primarily utilizes soil water from the upper soil layers. Black plastic mulch has been shown to maintain higher soil moisture content in the top soil layer (0–15 cm) compared to bare soil, with the greatest moisture conservation occurring at 10 cm depth.

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The water-saving potential of mulching is substantial. In the Arba Minch region of Ethiopia, straw mulching conserved, on average, 64.50 mm and 262.75 mm of water under 100% and 50% water application levels, respectively, compared to non-mulched treatments. Similarly, straw mulching with full irrigation reduced watermelon water consumption by 20.1% compared to the control treatment, and decreased total water use by 17% under 50% deficit irrigation compared to non-mulched treatment.

3.2 Interactions Between Mulch Type and Deficit Irrigation

Different mulch types exhibit varying effectiveness depending on irrigation level and environmental conditions. Research conducted in Jiroft, Iran, demonstrated that the highest yield (60.1 $t \cdot ha^{-1}$) was observed with full irrigation and plastic mulch, while the highest water productivity (15.1 $kg \cdot m^{-3}$) was recorded under 70% irrigation with plastic mulch. The study further revealed that the effectiveness of plastic mulch on watermelon growth and yield was higher with 100% and 70% irrigation compared to 50% irrigation.

Straw mulch, while superior to bare soil under full irrigation, had insignificant positive effects under severe deficit irrigation in some studies, potentially due to its high sodium content or slower breakdown rates under water-limited conditions. However, other research has demonstrated that straw mulching combined with 50% deficit irrigation can be highly effective for certain varieties, particularly in semi-arid regions.

The interaction between mulch type and irrigation level has important practical implications. Black plastic mulch appears to be most effective when combined with moderate deficit irrigation (70% of crop water requirement), while straw mulch may be more suitable for organic production systems or where plastic disposal is a concern.

3.3 Soil Temperature and Weed Suppression Effects

Beyond soil moisture conservation, mulching provides additional benefits including soil temperature regulation and weed suppression. Black plastic mulch increases soil temperature in the root zone during the early growing season, promoting faster plant growth and development. Organic mulches such as straw and date palm leaves moderate soil temperature, preventing excessive heating during hot periods.

Weed suppression is another important benefit of mulching. Plastic mulches provide complete weed control, while organic mulches reduce weed emergence through physical barrier effects. The combined effects of improved soil moisture, favorable temperature, and weed suppression contribute to enhanced crop growth and yield under mulched conditions.

4. Integrated Strategies: Combining Deficit Irrigation and Mulching for Optimal Production

The integration of deficit irrigation and mulching represents one of the most promising approaches for achieving sustainable watermelon production under increasing water scarcity. Numerous studies have demonstrated that combining these two technologies produces synergistic effects, resulting in higher water use efficiency than either practice applied independently. Mulching conserves soil moisture and reduces evaporation, allowing deficit irrigation to be implemented with minimal plant stress. Field experiments indicate that combining drip irrigation at approximately 75–80% crop evapotranspiration with black polyethylene mulch can reduce irrigation water requirements by 30–40% while maintaining fruit yields comparable to fully irrigated systems. Similarly, organic mulches combined with regulated deficit irrigation improve soil moisture retention, increase root-zone water availability, and reduce irrigation frequency throughout the growing season.

Integrated water management practices also improve nutrient use efficiency by minimizing nutrient leaching and maintaining favorable soil moisture conditions for nutrient uptake. Improved root growth under mulched conditions enhances nutrient absorption, while optimized irrigation prevents excessive nutrient losses associated with over-irrigation. Consequently, integrated strategies contribute to higher fertilizer use efficiency and lower environmental pollution. Recent technological advances involving precision agriculture, Internet of Things (IoT) sensors, automated irrigation controllers, drone-based crop monitoring, satellite remote sensing, and artificial intelligence have further enhanced integrated irrigation management. Smart irrigation systems continuously monitor soil moisture, crop water status, weather conditions, and evapotranspiration rates to determine optimal irrigation schedules. Such

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technologies support site-specific irrigation management, improving resource efficiency while reducing labor requirements.

Future research should focus on developing biodegradable mulching materials, climate-resilient irrigation scheduling algorithms, machine learning-based irrigation prediction models, and renewable energy-powered irrigation systems suitable for smallholder farmers. The integration of precision irrigation with environmentally sustainable mulching materials will play a vital role in addressing global water scarcity while ensuring food security and sustainable horticultural production.

4.1 Yield and Water Productivity Under Integrated Management

The integration of deficit irrigation and mulching offers the greatest potential for achieving optimal watermelon production with limited water resources. In the Hexi Oasis study, all water deficit treatments increased irrigation water use efficiency compared to full irrigation, with the highest IWUE recorded in the T2 treatment ($0.78\ t•ha^{-1}•mm^{-1}$), significantly higher by 10.50% than the control.

The AquaCrop model, validated in multiple studies, has proven to be a reliable tool for predicting watermelon productivity under deficit irrigation and mulching conditions. The model demonstrated acceptable performance with average R^2 and Nash-Sutcliffe efficiency (NSE) values of 0.84 and 0.74, respectively, for simulating evaporation, transpiration, and evapotranspiration. This model provides a valuable decision-support tool for optimizing irrigation strategies in water-limited environments.

Multi-objective optimization approaches, combining entropy weight with fuzzy matter-element models, have been employed to identify optimal deficit irrigation patterns based on yield, quality, and water use efficiency. The entropy weight–fuzzy matter-element comprehensive evaluation showed that the T2 treatment (mild deficit at seedling stage and moderate deficit at maturity stage) had the highest comprehensive score, followed by the T1 treatment. This approach helps balance trade-offs between conflicting objectives and identify strategies that achieve water-saving and high-quality production.

4.2 Varietal Selection and Rootstock Effects

The effectiveness of integrated deficit irrigation and mulching strategies depends significantly on varietal selection and rootstock choice. Research has demonstrated substantial varietal differences in water stress tolerance and yield response to deficit irrigation.

In the Arba Minch study, the Green Pearl variety consistently exhibited the highest productivity under various irrigation and mulching treatments, while the Lady Bell variety showed the highest sensitivity to water stress. The combination of 50% deficit irrigation with straw mulching and Green Pearl variety emerged as the most water-saving and productive irrigation practice, yielding the highest benefit-cost ratio (2.90), making it an economically viable choice for smallholder farmers.

Rootstock selection also plays a critical role in drought tolerance. Wild watermelon rootstock has been identified as a potential source of drought tolerance, with grafted plants demonstrating higher CWSI thresholds, lower yield response factors, and significantly increased water use efficiency under water stress. Plant growth-promoting rhizobacteria (PGPR), particularly Paenarthrobacteraurescens, have also been shown to enhance yield by up to 20% under severe water stress through the secretion of ACC deaminase, which reduces ethylene levels and promotes root growth.

4.3 Economic Considerations and Practical Implications

The economic viability of integrated deficit irrigation and mulching strategies is a critical consideration for adoption, particularly among smallholder farmers in water-limited regions. Benefit-cost analyses from the Arba Minch study revealed that the combination of half-level water application with straw mulching and Green Pearl watermelon varieties yielded the highest benefit-cost ratio (2.90), making it economically viable.

The cost of mulching materials and their potential environmental consequences must be considered when recommending specific strategies. While plastic mulch provides superior water conservation and weed control benefits, its disposal and potential for

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plastic pollution are growing concerns. Organic mulches such as straw and date palm leaves offer a more sustainable alternative, though their effectiveness may be lower under certain conditions.

A balanced approach, considering water availability, input costs, environmental impacts, and market requirements, is essential for the successful adoption of deficit irrigation and mulching strategies. In areas where water scarcity is severe, the 70% irrigation level with plastic mulch may be the most practical choice for maximizing water productivity, while the 100% irrigation level with black plastic mulch may be preferred when water is readily available.

5. Conclusion

This review examined the yield and water use responses of watermelon to deficit irrigation and mulching practices across diverse agro-ecological regions. Key findings reveal that strategic deficit irrigation significantly improves irrigation water use efficiency without compromising yield, with the T2 treatment (mild deficit at seedling stage combined with moderate deficit at maturity) achieving the highest IWUE of 0.78 $t \cdot ha^{-1} \cdot mm^{-1}$, a 10.50% increase over full irrigation, while maintaining comparable yields. Deficit irrigation also enhances fruit quality, increasing soluble solids, sugars, vitamin C, and soluble protein contents, particularly under moderate water stress during maturity. Mulching conserves soil moisture and reduces water consumption, with straw mulching conserving up to 262.75 mm of water under 50% deficit irrigation compared to non-mulched treatments. Integrated strategies combining deficit irrigation (70-75% of full irrigation) with mulching especially black plastic or straw mulch provide optimal balance between yield, water savings, and economic returns, achieving the highest water productivity of 15.1 $kg \cdot m^{-3}$ with 70% irrigation and plastic mulch. Varietal selection and rootstock choice are critical, with Green Pearl variety demonstrating superior productivity and tolerance, while grafting onto wild watermelon rootstock enhances drought tolerance and yield stability. The validated AquaCrop model offers a reliable tool for optimizing irrigation strategies in water-limited environments. Future research should refine integrated strategies for specific agro-ecological zones, evaluate long-term sustainability of mulching, and develop farmer decision-support tools, while policy must prioritize water-saving infrastructure, drought-tolerant varieties, and farmer training programs.

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ISSN (online): 3139-1494
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Citation of this Article:

Nivetha Thomas, & Sai Krishna M. (2026). Water-Saving Strategies for Watermelon Production: A Review of Deficit Irrigation and Mulching Effects on Yield and Water Use. *Journal of Recent Trends in Agriculture and Natural Sciences.* 2(2), 9-17. Article DOI: https://doi.org/10.47001/JRTANS/2026.202002

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