Deficit Irrigation for Watermelon: Water-Saving, Quality Improvement and Regional Food Security in Arid China

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Abstract. Watermelon is a distinctive economic crop that combines both nutritional value as a fruit/vegetable and industrial processing potential. It has played a significant role in improving the agricultural industrial structure and increasing agricultural projects. In the face of increasingly severe water resource shortages and frequent droughts in China's arid and semi-arid regions, the advancement of irrigation technology has compensated for the typical water resource shortage in China's arid areas. This paper conducts a methodological analysis of deficit irrigation (DI) in watermelon production in typical arid regions of China. With the background of water deficit at different growth stages of watermelon, it takes "high-yield, water use efficiency (WUE), and quality as indicators" to provide theoretical advantages and technical support in an effective and progressive manner, promoting the sustainable development of the fruit industry and expanding safety.

Keywords: Watermelon; Deficit irrigation; Water-use efficiency; Fruit quality; Arid region

1 Introduction

1.1 Water-Saving Agriculture and Food Security Support

Food safety (FS) is all about how we can reliably and sustainably obtain food that is safe and nutritious for osdur physical, social and economic well-being, in line with people' s safety and food records as well as food improvements [1]. In recent years, as a major agricultural country, China has consistently prioritized food security in the global food system. Major challenges are brought about by driving factors such as climate change, frequent high-impact climate events and evolving geopolitical conditions [2]. Crops like watermelon are playing a historically significant role and having a major impact on promoting the sustainability and stability of the agricultural sector.

Watermelon (Citrullus lanatus) is broadly grown across China due to its strong resilience to diverse environmental conditions, rapid maturation, and notable economic returns, positioning it as a crucial commercial crop in arid and semi-arid zones [3]. By 2022, the cultivated area for watermelon in China had expanded to nearly 1.5 million hectares, producing over 60 million tons annually—more than 60% of the world's total

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B. P. Siba et al. (eds.), *Proceedings of the 2026 5th International Conference on Public Service, Economic Management and Sustainable Development (PESD 2026)*, Advances in Economics, Business and Management Research 411,
https://doi.org/10.2991/978-94-6239-825-2_52

supply [4]. Despite its agricultural importance, watermelon is highly susceptible to drought, primarily because of its shallow root architecture and elevated water needs during critical developmental phases, especially fruit development [5]. Most of the country's principal watermelon-growing regions are located in ecologically vulnerable, water-scarce areas, including Northwest and North China, where natural freshwater resources are limited. The persistent use of traditional flood irrigation techniqueshas contributed to extensive water loss [6]. With mounting pressure on irrigation water supplies, the widening gap between water demand and availability in watermelon cultivation has intensified, emerging as a critical barrier to the sector's sustainable advancement.

1.2 DI Research Significance

DI, a proven water-efficient agricultural practice, has been broadly adopted in staple crops including wheat, maize, and potato, delivering substantial improvements in water conservation and yield consistency [7]. Nevertheless, watermelon responds to DI in a manner distinct from cereals, owing to its specific developmental physiology and high standards for fruit quality. As such, there is a pressing need to conduct systematic research on the impacts of DI in watermelon cultivation, identify the most suitable growth stages and levels for controlled water deficit, and develop an integrated production system that enhances both water use efficiency and fruit quality. Such advancements are vital for strengthening regional agricultural economies, increasing rural incomes, and supporting the transition toward sustainable irrigation practices (see Fig. 1).

Determining the most effective growth stages and levels for deficit irrigation in watermelon, along with establishing a cultivation strategy that balances water efficiency and superior fruit quality, can greatly decrease agricultural water demand and ease the strain on limited water resources in arid areas. Concurrently, this approach boosts the profitability of watermelon farming through enhanced produce quality [9]. Such progress is vital for supporting regional agro-economic resilience, raising rural household incomes, advancing efficient irrigation methods, and maintaining the environmental sustainability of dry land agricultural systems.

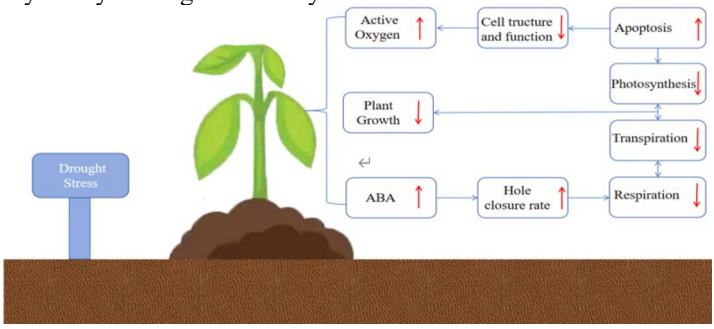


Fig. 1. Morphological performance of plants under drought conditions.

2 Water-Saving Agriculture and Food Security Coordination

2.1 Overview of DI

DI is a strategic water management approach in which irrigation is intentionally reduced during crop growth stages that are less sensitive to water stress, inducing controlled drought conditions to optimize water use efficiency, enhance resource productivity, and improve crop quality [8]. Originating in the 1970s, the concept of DI has undergone significant evolution over the past decades enabling accurate monitoring and regulation of soil moisture levels as well as coordinated water and nutrient management [9].

In arid environments, the essence of DI technology centers on determining the critical growth stages when crops require adequate water supply [9]. By maintaining sufficient irrigation during these sensitive periods while applying controlled water deficits during less vulnerable stages, DI effectively minimizes irrigation volume and

modulates key physiological and biochemical processes in plants, leading to enhanced water use efficiency (WUE) and improved product quality [10]. For watermelon cultivation, it is crucial to understand how growth dynamics, yield formation, and quality attributes respond to water stress at various developmental phases, enabling the development of scientifically sound and practical DI strategies (see Fig. 2).

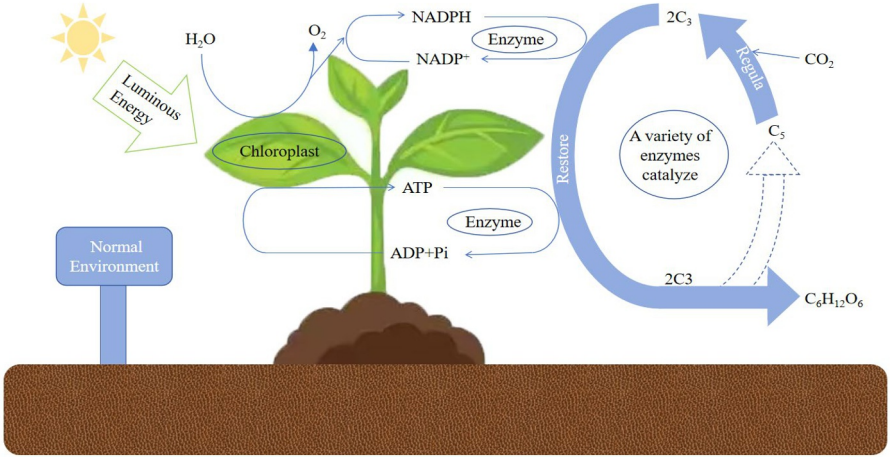


Fig. 2. Morphological performance of plants under appropriate water and nitrogen regulation.

2.2 Water-Saving Irrigation Safeguards Food Security

China faces severe water scarcity on a per capita basis, driven by a combination of rapid population growth, uneven geographical distribution of water resources, and increasing demands from industrial and agricultural sectors [7]. With freshwater resources amounting to roughly 2000 cubic meters per person annually—well below the global average—and dropping further in northern regions where agriculture is most intensive, the pressure on water supplies continues to intensify. Agricultural irrigation alone

accounts for more than 60% of the country's total water consumption, making it the largest single user of water nationwide [9]. However, the efficiency of water use in Chinese agriculture remains alarmingly low, estimated at around 50%, largely due to outdated irrigation infrastructure, reliance on flood irrigation methods, and limited adoption of precision technologies [11].

In contrast, advanced agricultural systems in developed countries often achieve irrigation efficiencies exceeding 70–80% through widespread use of drip irrigation, sprinkler systems, soil moisture sensors, and data-driven farm management practices. This significant gap underscores the urgent need for modernization in China's agricultural water management (see Fig. 3) [22]. In response, the government has prioritized water-saving initiatives, including the promotion of water-efficient crop varieties, expansion of piped irrigation networks, and investment in smart farming technologies. Large-scale projects such as the "Efficient Water-Saving Irrigation Action Plan" aim to improve field-level water productivity and reduce wastage across key grain-producing regions [12].

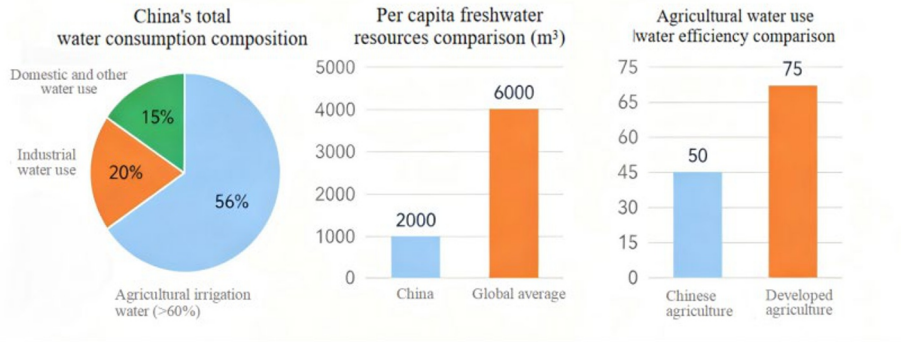


Fig. 3. Analysis of china's water resources utilization efficiency and per capita freshwater distribution [22].

The watermelon industry, as a key component of cash crop agriculture, plays a vital role in maintaining the stability of the agricultural economy. DI, a well-established water-saving technique, can reduce irrigation water use by 20%-30% compared to conventional methods while enhancing fruit quality—such as sugar concentration and flavor—when properly managed [12]. This approach not only helps relieve pressure on limited water resources but also increases the economic returns of watermelon cultivation, making it highly significant for ensuring diversified food supplies and securing farmer incomes in China's arid and semi-arid regions.

3 Effects of DI on Watermelon Production

3.1 Water Consumption Characteristics

The growth cycle of watermelon is typically categorized into four phases: seedling stage (SG), vine extension stage (VE), flowering and fruit setting stage (FFS), and fruit

expansion and ripening stage (FER). Water requirements vary considerably across these stages. Research indicates that water usage during SG represents 10%–15% of total seasonal consumption, VE accounts for 25%–30%, FFS consumes 20%–25%, while FER requires 35%–45%, making it the most critical period for water demand [13].

During the seedling stage, water demand is relatively low and primarily serves to sustain basic physiological functions [13]. During the vine elongation phase, as the plant rapidly expands, water consumption gradually increases [13]. The flowering and fruiting stage exhibits high sensitivity to water; insufficient moisture can lead to poor pollination and flower/fruit drop [17]. In contrast, during fruit enlargement and maturation, rapid cell division and expansion result in a sharp increase in water requirements, typically accounting for over 50% of total water consumption throughout the growth cycle, making this phase critical for determining yield and quality [17].

3.2 Yield and WUE

The effect of DI on watermelon yield and WUE is closely related to the deficit period and deficit degree. Moderate DI during non-critical growth periods can improve WUE without significantly reducing yield, while severe deficit or deficit during critical periods will lead to a sharp decline in yield [15]. Chen et al. (2025) found that that during different growth stages, using light drip irrigation (with a water application rate of 60%) compared to full irrigation reduced citrus yields in southern China by 8.5%, yet improved water use efficiency (WUE) and irrigation efficiency by 33.3% and 28.8%, respectively [14]. Studies demonstrate that soil moisture management based on matric potential (as demonstrated in strawberry cultivation) enables precise control of the water status in the root zone, thereby optimizing it without significantly compromising final fruit quality [15]. However, long et al. (2023) pointed out that severe DI (less than 50% FC) at the flowering and FFS or FER would reduce the yield by more than 30%, and the WUE also decreased significantly [16]. In addition, watermelons have a certain compensatory growth effect after rehydration under moderate DI. Yoonah J et al. (2019) found that after mild DI at the SG, rehydration at the VE could restore the growth status of watermelon, and the final yield reduction was less than 5%, while the WUE was significantly improved [17]. This indicates that rational use of the compensatory effect of watermelon can achieve the dual goals of water-saving and yield stabilization.

3.3 Fruit Quality

With the improvement of consumers' living standards, the demand for superior-grade watermelon is increasing. DI is an effective way to regulate watermelon fruit quality. Studies have shown that moderate DI during the appropriate period can significantly improve the soluble solids content, sugar-acid ratio, vitamin C and other quality indicators of watermelon, while excessive deficit will have a negative impact on quality.Yoonah et al. (2019) pointed out that mild to moderate DI at the flowering and FFS could improve the flavor and taste of watermelon, but deficit at the FER would lead to small fruit size, hard flesh and reduced edible quality [17]. The main reason is that

moderate DI regulates the synthesis and accumulation of carbohydrates and secondary metabolites in watermelon fruits by affecting the photosynthetic rate and transpiration rate of plants.

Furthermore, water regulation can indirectly influence the distribution and concentration of mineral elements in fruits by altering the root system's nutrient absorption efficiency [18]. For instance, moderate water control during fruit enlargement promotes the transport of key elements such as potassium and calcium to the flesh, thereby enhancing its crispness and storage stability [23]. However, the timing and intensity of regulation must be precisely calibrated, as different varieties exhibit varying responses to water stress, and environmental factors like soil type and climate conditions significantly modulate regulatory effects. Therefore, developing dynamic, personalized water management strategies based on real-time soil moisture monitoring and crop physiological data has become essential for achieving high-quality and efficient watermelon production.

4 DI Response Impact Factors of Watermelon

4.1 DI Complexity and Influencing Factors

Water scarcity significantly constrains the sustainable growth of the watermelon industry in China's arid regions. DI, recognized as an effective water-saving technique, holds considerable potential for application in watermelon cultivation [16]. By appropriately managing the timing and extent of water deficit, DI can simultaneously achieve water conservation, enhanced productivity, and improved fruit quality. However, watermelon's response to DI is highly complex and influenced by multiple factors, including cultivar type, soil properties, climatic conditions, and specific agronomic practices.

However, there are still some problems in the application of deficit irrigation in watermelon production. Firstly, the response of different watermelon varieties to DI varies greatly, and there is no unified DI standard. Secondly, it is difficult to accurately grasp the deficit period and degree in actual production, which requires long-term field experiments and monitoring. Thirdly, in saline-alkali areas, DI may lead to the accumulation of soil salts, aggravating salt stress on watermelon [21]. In addition, the popularization and application of DI technology are restricted by factors such as farmers' technical level and irrigation equipment conditions.

4.2 Practical Application Bottlenecks

To address these issues, several strategies can be implemented. For the lack of a unified DI standard for different watermelon varieties, extensive research should be carried out to establish variety-specific DI guidelines. This can involve conducting controlled experiments on a wide range of watermelon cultivars to determine their optimal water deficit levels at different growth stages. Regarding the difficulty in accurately determining the deficit period and degree, advanced technologies such as soil moisture sensors and remote sensing can be utilized. These tools can provide real-time data on soil moisture and plant water status, enabling farmers to make more informed decisions

about irrigation scheduling. In saline-alkali areas, measures like leaching irrigation can be combined with DI to prevent salt accumulation. Leaching irrigation can flush out excess salts from the root zone, reducing the salt stress on watermelon plants. Moreover, to overcome the restrictions posed by farmers' technical level and irrigation equipment conditions, training programs and subsidies can be provided. Training can enhance farmers' understanding of DI technology and its benefits, while subsidies can encourage them to invest in better irrigation equipment, facilitating the wider adoption of DI in watermelon production.

4.3 Optimal Deficit Stage and Intensity

Current research shows that the SG and VE of watermelon are the optimal deficit periods, and the appropriate deficit degree is 55%-65% of field capacity [19]. Currently, the yield reduction is within an acceptable range, and the WUE and fruit quality are significantly improved. Watermelon requires substantial water during key growth stages, particularly from flowering through fruit set and during fruit expansion. To support optimal development and maximize yield, DI should be minimized or avoided entirely during these critical periods [17].

Moreover, deficit irrigation (DI) during non-critical periods can enhance the concentration of soluble solids, vitamins, and antioxidants in the fruit, thereby improving its nutritional value and market appeal [19]. However, it is crucial to carefully monitor soil moisture levels to prevent excessive water stress, which can lead to undesirable effects such as fruit cracking, reduced size, and poor flavor [20]. By fine-tuning the timing and intensity of DI, growers can achieve a balance between water conservation and high-quality watermelon production.

5 Conclusion

Water scarcity constitutes a major constraint on the sustainable development of the watermelon industry in China's arid regions. DI, as an efficient water-saving irrigation technology, has broad application prospects in watermelon production. By appropriately adjusting the timing and extent of water deficit, significant improvements in water conservation, production efficiency, and fruit quality can be achieved. Nevertheless, the physiological response of watermelon to DI is highly intricate and influenced by various factors, including cultivar type, soil characteristics, climatic conditions, and agricultural management practices.In the future, it is necessary to strengthen the research on the response of different watermelon varieties to DI, clarify the physiological and molecular mechanisms of DI regulating watermelon yield and quality, and establish a precise deficit irrigation technology system suitable for different regions. Meanwhile, there is a pressing need to accelerate the dissemination and implementation of DI technology, enhance farmers' technical capabilities, and facilitate its integration with modern agricultural systems such as water-fertilizer coupling and Internet of Things-based monitoring.

Acknowledgments

This work was mutually supported by the Science Foundation of Shandong Province (No. ZR2024MC190), the Scientific Research Foundation for High-level Talented Scholars of Liaocheng University (No. 318042401), and the National Natural Science Foundation of China (No. 52269008, 51669001).

References

1. L. Durano, M Sarmiento, G. D. A. Romo, et al. Food security of agri-food system actors during the COVID-19 pandemic in the Philippines: Post-pandemic implications to sustainable development. J. Journal of Agriculture and Food Research. 18 (2024
2. M. Ben Rabha, M.F. Boujmil, M. Saadoun, B. Bessaïs, Eur. Phys. J. Appl. Phys. (to be published) https://doi.org/10.1051/epjap/2009085W. Yue, M. Su, Y. Cai, et al. Merits of dietary patterns for China's future food security satisfying socioeconomic development and climate change adaptation. J. iScience, 28 (2025).
3. M. V. Castellote, D. P. Marín, I. T. Rodríguez , et al. Corrigendum to "Implementing near infrared spectroscopy for the online internal quality and maturity stage classification of intact watermelons at industry level" [Spectrochim. Acta A Mol. Biomol. Spectrosc. 339 (2025) 126254]. J. Spectrochimica acta Part A, Molecular and biomolecular spectroscopy, 349 (2025).
4. J. Peng, W. Liu, Y. Gao, et al. Elucidating nitrogen-doping mediated pollutant removal in flow-electrode capacitive deionization for copper-sulfate-rich wastewater treatment. J. Chemical Engineering Journal, 525 (2025).
5. Y. Meng, Q. Ding, L. Jia, et al. Map-based cloning and functional validation of ClChlH governing yellow rind color in watermelon (Citrullus lanatus). J.TAG Theoretical and applied genetics Theoretische und angewandte Genetik , 12 (2025).
6. K. Singh, H. Liao, I. Edirisinghe, et al. Dose-Response Effect of Watermelon Consumption on Ambulatory Blood Pressure in Adults with Elevated Blood Pressure: A Randomized Controlled Pilot Trial. J. Nutrients, 17 (2025).
7. D. A. Larky, S. Mohammadi, S. A. H. Mousavi, et al. Effects of Citrulline or Watermelon Supplementation on Body Composition: A Systematic Review and Dose-Response Meta-Analysis. J.Nutrients, 17 (2025).
8. A. Khalofah, M. Q. N. Khan, H. S. Hayat. Mitigation Potential of Green-Zinc Oxide Nanoparticles for Nickel (Ni) Stress in Watermelon Plants: Regulation of Cellular Oxidative Stress Metabolism and Reduction in Ni Translocation. J. Journal of Soil Science and Plant Nutrition, 25 (2025).
9. X. Liu, J. Zuo, J. Tao, et al. A multi-omics dissection of the molecular mechanisms underlying water soaking in fresh-cut watermelon. J. Molecular horticulture, 20 (2026)
10. Y. Gaopeng, L. Junpu, A. Guolin, et al. Genome-Wide Identification and Characterization of the Trehalose-6-phosphate Synthetase (TPS) Gene Family in Watermelon (Citrullus lanatus) and Their Transcriptional Responses to Salt Stress. J. International Journal of Molecular Sciences, 23 (2021).
11. O. M. Iniaghe, O. Ibukun. Evaluation of the Effects of Some Metal Chlorides on the Initial Reaction Rate of Crude Peroxidase from Watermelon Peels. J. Asian Journal of Biotechnology and Bioresource Technology, 9 (2023).

12. N. Yavuz, M. Seymen, Ü. Kal, et al. Interactive effects of rootstock and rhizobacteria on fruit yield, evapotranspiration, and the crop water stress index (CWSI) in watermelon under water deficit stress. J. Plant and Soil, 513 (2024).
13. H. A. S. Hashmi, H. M. Asif, K. Ahmad, et al. Combined computational and pharmacological approach reveals Citrullus colocynthis as a natural PCSK9 inhibitor in insulin resistant rats. J. Pakistan journal of pharmaceutical sciences, 38 (2025).
14. F. Chen, N. Cui, S. Jiang, et al. Effects of deficit drip irrigation at different growth stages on citrus leaf physiology, fruit growth, yield, and water productivity in South China. J. Agricultural Water Management, 307 (2025).
15. Guillaume Létourneau, J. Caron, L. Anderson, J. Cormier. Matric potential-based irrigation management of field-grown strawberry: Effects on yield and water use efficiency. J. Agricultural Water Management, 161 (2015).
16. L. Longxiang, Z. Yumiao, L. Junhua, et al. Exploring the changes in microorganisms and metabolites during the fermentation process of traditional Chinese watermelon–soybean paste. J. LWT, 188 (2023).
17. J. Yoonah, M. JiHye, K. SangGyu, et al. Effect of Low-Temperature Tolerant Rootstocks on the Growth and Fruit Quality of Watermelon in Semi-Forcing and Retarding Culture. J. Agronomy, 13 (2022).
18. P. Sakha, F. M. Ali, H. S. Abolfazl, et al. Pesticide content analysis of red and yellow watermelon juices through a solid phase microextraction using a green copper-based metal-organic framework synthesized in water followed by a liquid phase microextraction procedure. J. Analytical sciences: the international journal of the Japan Society for Analytical Chemistry, 39 (2022).
19. M. Takudzwa, O. A. Oduor, M. Jacob, et al. Phenotypic Variability of Root System Architecture Traits for Drought Tolerance among Accessions of Citron Watermelon (Citrullus lanatus var. citroides (L.H. Bailey). J. Plants, 19 (2022).
20. N. Maham, N. Muhammad, Q. T. Mahmood, et al. The Synergistic Effects of Sonication and Microwave Processing on the Physicochemical Properties and Phytochemicals of Watermelon (Citrullus lanatus) Juice. J. Agriculture, 12 (2022).
21. V. S K, G. E A, A. E Y, et al. Analysis of the Genes That Determine the Dwarf Form of Watermelon Citrullus lanatus (Thunb.) Matsum. Nakai in the VIR Collection. J. Russian Journal of Genetics, 58 (2022).
22. Z. Xiaheng, L. Zekai. Evaluation of Water Resource Utilization Efficiency in Provincial Areas of China Based on the Unexpected Output SBM Model. J. Journal of environmental and public health, 1 (2022).
23. Omotayo B Adeboye, Bart Schultz, Kenneth O Adekalu, Krishna Prasad. Crop water productivity and economic evaluation of drip-irrigated soybeans (Glyxine max L. Merr.). J. Agriculture & Food Security, 4 (2015).

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