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Optimizing Deficit Irrigation Management to Improve Potato Yield, Quality and Water Use Efficiency: A Review

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Abstract: Potatoes, as a vital staple crop, are integral to maintaining food supply and economic resilience. In China, they are predominantly grown in arid and semi-arid zones, where water scarcity and limited precipitation hinder sustainable cultivation. Deficit irrigation has emerged as a practical approach to enhancing water use efficiency while sustaining desirable yields and tuber quality. Nonetheless, current literature reveals gaps in understanding the physiological and agronomic responses of potatoes under such water-limited conditions. This review synthesizes existing findings on how deficit irrigation influences potato yield and quality, and examines strategies to improve irrigation management. It also outlines potential directions for future investigations, aiming to offer theoretical support for efficient potato farming in drought-prone regions.

Keywords: deficit irrigation; water consumption patterns; yield and quality; water productivity; potato

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1. Introduction

Food security remains a cornerstone of human survival and socio-economic development. In recent years, intensified climate warming and accelerated global water cycles have led to frequent extreme droughts, which have negatively affected agricultural productivity worldwide [1]. This issue is particularly severe in regions facing water scarcity, where droughts consistently result in crop yield losses and significant economic setbacks [2]. Balancing national food security with the pursuit of sustainable agriculture has thus become a pressing concern for the global research community. Among the various approaches proposed, deficit irrigation has emerged as an effective means to reconcile the imbalance between limited water availability and crop demand, while improving water use efficiency in arid environments [3]. This method involves the deliberate application of reduced water during certain growth stages based on crop-specific water requirements, aiming to preserve yield and quality while enhancing water productivity [4].

Potato (Solanum tuberosum L.), as one of the most important global food crops, plays a vital role in food supply and economic growth [5]. Its wide range of varieties, high yield potential, and adaptability distinguish it from many other staple crops. China, accounting for about 25% of global potato output, leads the world in production volume [6]. Despite its adaptability to different climates, potato cultivation is highly dependent on water availability due to the crop's shallow root system and sensitivity to soil moisture [7]. In arid zones, irrigation is essential for maintaining productivity. In response to the ongoing challenges of low yield and inefficient water use in these areas, researchers have increasingly explored the application of deficit irrigation in potato farming. However, the response of potatoes to water stress has proven inconsistent, with variability in yield, quality, and physiological traits under different environmental conditions and irrigation regimes.

Although many field experiments on potato deficit irrigation have been conducted in arid regions, comprehensive reviews that consolidate and interpret these results remain limited. This study aims to bridge that gap by summarizing potato-specific water needs, evaluating the effects of deficit irrigation on yield and tuber quality, identifying obstacles to optimizing irrigation schedules, and proposing future research directions. Ultimately, the review seeks to support more efficient irrigation strategies and promote sustainable potato cultivation in water-limited regions.

2. Water Consumption Patterns in Potatoes

The complete growth cycle of potatoes is generally divided into five distinct stages: seedling, tuber initiation, tuber bulking, starch accumulation, and maturity [8]. Water demand is relatively low during the seedling and starch accumulation phases, accounting for approximately 15% and 10% of the total water usage during the reproductive period, respectively [9]. In contrast, the tuber initiation and tuber bulking stages exhibit significantly higher water requirements, comprising around 25% and 50% of total water use during this period. This trend has been confirmed by previous studies, which show that potato water consumption increases early in the reproductive phase, peaks during tuber bulking, and then gradually declines [10].

Daily water use also varies across growth stages. Reported average daily consumption rates range from 1.54-2.79 mm during germination, 1.67-3.14 mm during the seedling stage, 2.84-5.59 mm during tuber formation, and reach 4.77-5.91 mm during tuber bulking — the stage with the highest demand. Rates then decrease to 3.49-4.89 mm during starch accumulation [11]. For spring-grown potatoes, the proportion of total water consumption during each phase is distributed as follows: 10.6% during seedling, 23.3% during tuber formation, a peak of 58% during tuber bulking, and just 8.14% during starch accumulation [12]. These findings collectively highlight tuber bulking as the most water-sensitive and critical stage for irrigation management.

Potato water demand is influenced by a range of factors, including geographic location, climate, and soil characteristics. Despite these variations, a general trend can be observed: water consumption and daily usage intensity typically increase during early reproductive stages, peak around tuber expansion, and then decline toward maturity. The tuber expansion phase consistently shows the highest values in both total water requirement and daily consumption rates. Given this, the tuber formation and expansion stages are particularly sensitive to water availability, making it essential to maintain sufficient irrigation during these periods to prevent significant yield reductions.

3. Impact of Deficit Irrigation on Potato Quality, Yield and Water Productivity

In practical agricultural production, crop yield and quality consistently represent the primary objectives pursued by growers. Numerous studies have demonstrated that deficit irrigation can enhance potato quality by promoting physiological changes within the plant that favor the development of desirable traits such as higher starch content, reduced tuber water content, and improved skin texture. However, it concurrently results in varying degrees of yield reduction, which presents a challenge for growers aiming to balance both quality and quantity in their harvests [13]. The reduction in yield is often attributed to the effects of water stress on key processes like tuber growth, photosynthesis, and nutrient uptake, which may be compromised when water supply is limited.

To reconcile the conflict between potato yield and quality, many researchers have sought to identify optimal irrigation strategies for potato cultivation through carefully designed experiments incorporating different levels of deficit irrigation. These strategies typically focus on optimizing water use efficiency while minimizing negative impacts on crop productivity. Several investigations indicated that water stress, especially during critical growth stages such as tuber initiation and bulking, can lead to an increase in tuber dry weight and the percentage of misshapen potatoes. Simultaneously, however, it has been shown to decrease overall yield per plant, the number of tubers per plant, harvest index, and fruit set rate [14]. These observations underscore the trade-off between maximizing yield and improving quality through water stress management.

On the other hand, it has also been observed that moderate water deficits during the starch accumulation stage in potatoes exert a non-significant effect on yield but lead to an increase in tuber starch content [15]. The starch content is one of the most critical quality parameters for potatoes, particularly for those intended for processing into products like chips or fries. Moderate water stress during this stage appears to favor the synthesis and accumulation of starch, thus improving the quality of the harvested tubers without a substantial sacrifice in yield. This phenomenon suggests that the timing and severity of water stress during the growing season play a significant role in determining both yield and quality outcomes.

Researchers have further demonstrated that maintaining a moderate water deficit (approximately 75% of crop requirements) throughout the full growing season significantly enhances water use efficiency, which is a crucial factor in areas where water resources are limited or where growers seek to optimize their input costs [16]. By reducing irrigation amounts while still maintaining reasonable crop growth, these strategies can help reduce water consumption while still achieving economically viable yields. Additionally, the application of such strategies may allow growers to maintain sustainable practices in water-scarce regions, where efficient water management is paramount.

Additionally, it was found that implementing mild water deficit treatments during the early seedling stage notably improved both water use efficiency and quality while ensuring yields through trials involving different growth stages of potato crops [17]. Water stress during the seedling stage appears to trigger adaptive responses in the plants, promoting deeper root systems and improving the plant's ability to access soil moisture more efficiently during later stages of growth. This early water deficit may also have a positive impact on the development of the tubers, improving both their size and quality by the time they reach harvest. The ability to ensure yield stability, even with reduced water inputs, adds significant value to such irrigation strategies, particularly in regions with limited water resources.

Furthermore, it was reported that applying a mild water deficit treatment (55-65% of field water holding capacity) during tuber formation led to significant improvements in irrigation water use efficiency, as well as commercial yields for potatoes while maintaining stable overall production levels [18]. This finding suggests that precise timing of water stress, especially during the tuber formation phase, could be key to achieving optimal irrigation strategies. During this phase, the plant is highly sensitive to water availability, and the implementation of mild deficit irrigation can enhance the plant's ability to manage water resources effectively, resulting in higher commercial yields and better quality tubers. These results reinforce the idea that targeted deficit irrigation can optimize both water use efficiency and crop productivity, offering practical benefits for growers.

In summary, while deficit irrigation has the potential to enhance potato quality, particularly in terms of starch content and tuber shape, it must be carefully managed to avoid detrimental effects on overall yield. The success of these irrigation strategies depends on the timing and severity of the water deficit, with moderate water stress at specific growth stages offering the best balance between yield and quality. As water scarcity becomes an increasingly pressing concern in many agricultural regions, these strategies provide a promising avenue for achieving sustainable, high-quality potato production while minimizing water usage.

4. Impact of Deficit Irrigation on Photosynthetic Indices in Potato

Photosynthesis in the leaves of water-stressed plants is significantly impacted, as water availability directly influences gas exchange processes and physiological metabolism. Generally, water deficit leads to a reduction in net photosynthetic rate, which can be attributed to two primary factors [19]. Firstly, under drought stress conditions, both transpiration rate and stomatal conductance are concurrently diminished. This observation suggests that the decline in net photosynthetic rate is primarily due to stomatal limitations within the leaf. In other words, drought stress induces partial or complete stomatal closure, resulting in decreased stomatal conductance and an inadequate supply of CO_2 substrate, thereby limiting the photosynthetic carbon assimilation process. Secondly, the observed increase in intercellular CO_2 concentration, despite decreases in transpiration rate and stomatal conductance, indicates that internal metabolic or biochemical limitations — known as non-stomatal restrictions — also contribute to the decline in net photosynthetic rate. These include impaired enzymatic activity (e.g., Rubisco), chloroplast structural damage, reduced electron transport efficiency, and degradation of photosynthetic pigments. In severe cases, drought stress can lead to photoinhibition and oxidative stress, which further exacerbate the loss of photosynthetic capacity [20].

Moreover, drought-induced changes in photosynthetic indices vary significantly among potato genotypes. Drought-tolerant varieties typically maintain higher levels of chlorophyll content, better integrity of photosystem II, and enhanced antioxidant enzyme activity under stress, all of which contribute to a relatively stable photosynthetic rate. It was reported that under drought conditions, drought-resistant potato varieties exhibited a comparatively smaller decline in their photosynthetic indices than susceptible varieties, highlighting the importance of genotype-specific physiological resilience [21].

In recent years, advancements in remote sensing and high-throughput phenotyping technologies have enabled more precise and dynamic monitoring of plant photosynthetic responses to water deficit at both leaf and canopy scales. Indices such as the Normalized Difference Vegetation Index (NDVI) and Photochemical Reflectance Index (PRI) have proven useful for assessing drought impacts on photosynthetic efficiency. Future studies should focus on integrating physiological measurements with remote sensing data and modeling approaches to better understand the spatial and temporal dynamics of photosynthetic responses under deficit irrigation. Additionally, identifying physiological traits linked to sustained photosynthetic activity under water-limited conditions can provide a theoretical foundation for breeding drought-resilient potato cultivars.

5. Irrigation Regime Optimization Methods

Selecting an appropriate irrigation strategy that optimally balances crop water productivity, tuber quality, and economic efficiency is critical. One study analyzed the water production function of potatoes under drip irrigation combined with film mulching using the Jensen model [22]. A genetic algorithm, implemented via MATLAB, was applied to determine the optimal irrigation strategy, highlighting the utility of intelligent algorithms in addressing nonlinear challenges in agricultural water management. In another approach, hierarchical analysis and fuzzy comprehensive evaluation were used to achieve multi-objective optimization, integrating metrics such as yield, water use efficiency, and economic benefits to define optimal irrigation and fertilization schedules for potato cultivation [23]. These methods offer a flexible decision-making framework suitable for complex and uncertain farming conditions.

Additionally, the DSSAT crop model was calibrated using field data from potato trials to evaluate its simulation accuracy [24]. The results showed that the calibrated model reliably replicated potato growth patterns and suggested an optimal total irrigation input of 350 mm for the Heihe River Basin. Simulation tools like DSSAT provide a scientific foundation for regional irrigation planning and allow for scenario analysis under diverse climatic and soil conditions. However, further refinement is needed to enhance their precision and adaptability to local conditions. Future research should also explore the integration of real-time sensor data and remote sensing technologies with model-driven decision systems to improve the accuracy and responsiveness of irrigation management in potato production.

6. Conclusions and Prospects

Deficit irrigation holds significant potential for promoting sustainable and efficient potato production in arid and semi-arid regions. Despite substantial global research on the impact of deficit irrigation on aspects such as potato growth, physiological and ecological indicators, yield, and quality, several key issues still require further exploration. One such issue is the close relationship between potato growth and soil conditions. Poorly designed irrigation systems can lead to soil compaction and salinization, negatively impacting potato growth and tuber quality. These adverse soil conditions can also increase disease susceptibility and reduce overall plant health, ultimately diminishing yield and profitability. Therefore, future research should prioritize the effects of different deficit irrigation levels on soil quality.

Another important factor is the varying sensitivity of potatoes to water deficits at different fertility stages, which directly influences yield and quality. Future studies should quantify these relationships by assessing the specific responses of both potato yield and quality to water deficits at different growth stages. Moreover, developing a comprehensive water-yield-quality production function will be crucial for accurately measuring the combined benefits of irrigation strategies.

Finally, while environmental factors play a critical role in potato growth, most existing studies provide theoretical insights without offering practical solutions for large-scale implementation. To address this gap, future research should focus on understanding the underlying mechanisms by which irrigation affects potato cultivation and develop effective extension programs for the adoption of deficit irrigation practices in agricultural outreach initiatives.

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References

1. R. L. Ray, A. Fares, and E. Risch, "Effects of drought on crop production and cropping areas in Texas," *Agric. Environ. Lett.*, vol. 3, no. 1, p. 170037, 2018, doi: 10.2134/ael2017.11.0037.
2. Y. Zhao, R. Zheng, F. Zheng, K. Zhong, J. Fu, J. Zhang, et al., "Spatiotemporal distribution of agrometeorological disasters in China and its impact on grain yield under climate change," *Int. J. Disaster Risk Reduct.*, vol. 95, p. 103823, 2023, doi: 10.1016/j.ijdrr.2023.103823.
3. D. S. K. Dingre and S. D. Gorantiwar, "Soil moisture based deficit irrigation management for sugarcane (Saccharum officinarum L.) in semiarid environment," *Agric. Water Manag.*, vol. 245, p. 106549, 2021, doi: 10.1016/j.agwat.2020.106549.
4. A. D. Nikanorova, E. V. Milanova, N. M. Dronin, and N. O. Telnova, "Estimation of water deficit under climate change and irrigation conditions in the Fergana Valley of Central Asia," *Arid Ecosyst.*, vol. 6, pp. 260–267, 2016, doi: 10.1134/S2079096116040053.
5. J. Tang, H. Yang, Y. Li, Y. Zhang, Z. Wang, and Y. Bai, "Identifying agronomic options for better potato production and conserving water resources in the agro-pastoral ecotone in North China," *Agric. For. Meteorol.*, vol. 272, pp. 91–101, 2019, doi: 10.1016/j.agrformet.2019.04.001.
6. A. Devaux, J. P. Goffart, P. Kromann, J. Andrade-Piedra, V. Polar, and G. Hareau, "The potato of the future: opportunities and challenges in sustainable agri-food systems," *Potato Res.*, vol. 64, no. 4, pp. 681–720, 2021, doi: 10.1007/s11540-021-09501-4.

7. C. Wagg, S. Hann, Y. Kupriyanovich, and S. Li, "Timing of short period water stress determines potato plant growth, yield and tuber quality," *Agric. Water Manag.*, vol. 247, p. 106731, 2021, doi: 10.1016/j.agwat.2020.106731.
8. M. W. Nasir and Z. Toth, "Effect of drought stress on potato production: A review," *Agronomy*, vol. 12, no. 3, p. 635, 2022, doi: 10.3390/agronomy12030635.
9. A. Eskandari, H. R. Khazaie, A. Nezami, M. Kafi, A. Majdabadi, and S. Soufizadeh, "Effects of drip irrigation regimes on potato tuber yield and quality," *Arch. Agron. Soil Sci.*, vol. 59, no. 6, pp. 889–897, 2013, doi: 10.1080/03650340.2012.685466.
10. H. Zhang, X. Chen, D. Xue, W. Zhang, F. Li, A. Teng, et al., "Dry matter accumulation, water productivity and quality of potato in response to regulated deficit irrigation in a desert oasis region," *Plants*, vol. 13, no. 14, p. 1927, 2024, doi: 10.3390/plants13141927.
11. A. Poddar, N. Kumar, and V. Shankar, "Evaluation of two irrigation scheduling methodologies for potato (Solanum tuberosum L.) in north-western mid-hills of India," *ISH J. Hydraul. Eng.*, vol. 27, no. 1, pp. 90–99, 2021, doi: 10.1080/09715010.2018.1518733.
12. F. Li, H. Zhang, X. Li, H. Deng, X. Chen, and L. Liu, "Modelling and evaluation of potato water production functions in a cold and arid environment," *Water*, vol. 14, no. 13, p. 2044, 2022, doi: 10.3390/w14132044.
13. B. Li and L. Shen, "Effects of soluble organic fertilizer combined with inorganic fertilizer on greenhouse tomatoes with different irrigation techniques," *Agriculture*, vol. 14, no. 2, p. 313, 2024, doi: 10.3390/agriculture14020313.
14. P. M. K. Deblonde and J. F. Ledent, "Effects of moderate drought conditions on green leaf number, stem height, leaf length and tuber yield of potato cultivars," *Eur. J. Agron.*, vol. 14, no. 1, pp. 31–41, 2001, doi: 10.1016/S1161-0301(00)00081-2.
15. C. Carli, F. Yuldashev, D. Khalikov, B. Condori, V. Mares, and P. Monneveux, "Effect of different irrigation regimes on yield, water use efficiency and quality of potato (Solanum tuberosum L.) in the lowlands of Tashkent, Uzbekistan: A field and modeling perspective," *Field Crops Res.*, vol. 163, pp. 90–99, 2014, doi: 10.1016/j.fcr.2014.03.021.
16. M. Kifle and T. G. Gebretsadakan, "Yield and water use efficiency of furrow irrigated potato under regulated deficit irrigation, Atsibi-Wemberta, North Ethiopia," *Agric. Water Manag.*, vol. 170, pp. 133–139, 2016, doi: 10.1016/j.agwat.2016.01.003.
17. F. Li, H. Deng, Y. Wang, X. Li, X. Chen, L. Liu, and H. Zhang, "Potato growth, photosynthesis, yield, and quality response to regulated deficit drip irrigation under film mulching in a cold and arid environment," *Sci. Rep.*, vol. 11, no. 1, p. 15888, 2021, doi: 10.1038/s41598-021-95340-9.
18. M. S. Waqas, M. J. M. Cheema, S. Hussain, M. K. Ullah, and M. M. Iqbal, "Delayed irrigation: An approach to enhance crop water productivity and to investigate its effects on potato yield and growth parameters," *Agric. Water Manag.*, vol. 245, p. 106576, 2021, doi: 10.1016/j.agwat.2020.106576.
19. K. K. Sarker et al., "Yield and quality of potato tuber and its water productivity are influenced by alternate furrow irrigation in a raised bed system," *Agric. Water Manag.*, vol. 224, p. 105750, 2019, doi: 10.1016/j.agwat.2019.105750.
20. T. Gervais, A. Creelman, X. Q. Li, B. Bizimungu, D. De Koeyer, and K. Dahal, "Potato response to drought stress: physiological and growth basis," *Front. Plant Sci.*, vol. 12, p. 698060, 2021, doi: 10.3389/fpls.2021.698060.
21. M. Alhoshan, A. A. Ramin, M. Zahedi, and M. R. Sabzalian, "Effects of water deficit on shoot, root and some physiological characteristics in some greenhouse grown potato cultivars," *J. Crop Sci. Biotechnol.*, pp. 1–12, 2020, doi: 10.1007/s12892-020-00051-8.
22. F. Li, H. Zhang, X. Li, H. Deng, X. Chen, and L. Liu, "Modelling and evaluation of potato water production functions in a cold and arid environment," *Water*, vol. 14, no. 13, p. 2044, 2022, doi: 10.3390/w14132044.
23. H. Wang, M. Cheng, S. Zhang, J. Fan, H. Feng, F. Zhang, et al., "Optimization of irrigation amount and fertilization rate of drip-fertigated potato based on Analytic Hierarchy Process and Fuzzy Comprehensive Evaluation methods," *Agric. Water Manag.*, vol. 256, p. 107130, 2021, doi: 10.1016/j.agwat.2021.107130.
24. Y. Zhao, G. Li, S. Li, Y. Luo, and Y. Bai, "A review on the optimization of irrigation schedules for farmlands based on a simulation–optimization model," *Water*, vol. 16, no. 17, p. 2545, 2024, doi: 10.3390/w16172545.