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Advancements in Research on the Impact of Deficit-Regulated Irrigation on Photosynthetic Characteristics, Yield, and Quality of Drip-Irrigated Potatoes under Film

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Abstract: Potato is an essential food and economic crop that contributes significantly to national food security. As the issue of water scarcity in agriculture becomes increasingly prevalent, research into appropriate irrigation systems to accomplish water conservation, high quality, and stable potato yield has attracted widespread attention. The physiological characteristics, growth patterns, and water use efficiency of potatoes at various reproductive stages exhibit distinct responses to deficit irrigation. This paper specifically examines the impact of deficit irrigation on photosynthetic traits, water use efficiency, and potato yield. The findings indicate that severe water deficits hinder the accumulation of photosynthetic products and dry matter in potatoes, ultimately leading to a reduction in yield. In contrast, timely and adequate irrigation promotes optimal growth conditions.

Keywords: deficit-regulated irrigation; potato; photosynthetic characteristics; water use efficiency; yield

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1. Introduction

The World Meteorological Organization (WMO) released the "State of the Global Climate 2023", which reveals a steady increase in global average temperatures from 1980 to 2023. Projections indicate that by 2023, the global near-surface temperature will rise by approximately 1.45°C compared to pre-industrial levels, with ongoing warming expected to significantly impact agricultural production and development [1-3]. In China, water resources are severely limited, with per capita availability being only a quarter of the global average. The proportion of water used in agriculture has decreased from 97.10% in 1949 to 62.2% in 2023, creating considerable challenges for agricultural production [4]. Continued warming will exacerbate the existing mismatch between agricultural water supply and demand. Therefore, adopting deficit-regulated irrigation is essential to improve crop water productivity and ensure sustainable agricultural water resource management.

Potato (Solanum tuberosum L.), a member of the Solanaceae family, is the fourth most significant food crop globally, after wheat, rice, and maize [5]. Rich in starch, protein, fats, and essential vitamins and trace elements, including B vitamins, vitamin C, and carotenoids, potatoes offer a nutritionally balanced food source [6]. This crop thrives in

cooler climates, requiring high temperatures, adequate water, and nutrients for optimal growth [7,8]. The Hexi oasis irrigation area, with its mild arid climate, is a crucial agricultural region in China, and potatoes have become a key economic driver. However, the traditional diffuse irrigation method has limited the efficiency of potato cultivation and constrained farmer incomes. To address this, deficit-regulating irrigation technologies, particularly sub-film drip irrigation, have been introduced. This method enhances water use efficiency and supports better root development, crop quality, and yield by precisely controlling irrigation and reducing water evaporation through film cover. Additionally, sub-film drip irrigation lowers production costs, mitigates rising water tables, conserves water resources, and promotes the sustainable development of agroecosystems. This paper offers a comprehensive overview of the effects of deficit-regulated irrigation on potato photosynthesis, water use efficiency, yield, and quality, while outlining future research directions to optimize water-saving irrigation techniques in potato farming.

2. Effect of Deficit-Regulated Irrigation on Photosynthetic Characteristics of Potato

Photosynthesis is fundamental to material and energy metabolism in plants, and is the primary mechanism for organic matter accumulation in green plants, directly influencing biomass production [9]. Understanding how crops respond to water stress — through changes in photosynthesis, stomatal conductance, and transpiration — is essential for assessing the impacts of water deficits on crop growth and development [10]. Field experiments using green potato 168 revealed that water deficit during different reproductive stages significantly reduced photosynthetic rate, stomatal conductance, and transpiration rate in potato leaves. The extent of these reductions was proportional to the severity of soil water deficit [11]. Deficit irrigation research under plastic greenhouse conditions showed that water stress led to significant reductions in net photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (Gs), and intercellular CO2 concentration (Ci) in potato leaves, with the trend observed as: control > moderate treatment > severe treatment. Water deficit not only affects photosynthetic characteristics but also alters the accumulation and distribution of dry matter. Under water stress, dry matter accumulation in maize roots, stems, and leaves declines, resulting in a reduced total dry matter accumulation [12]. Further studies found that soil water stress during potato tuber growth significantly decreased Pn, Tr, Gs, and Ci [13]. In summary, regulating deficit irrigation has a substantial impact on photosynthesis in drip-irrigated potatoes under membrane conditions, where the timely application of water deficits can enhance leaf photosynthetic rate, improve the allocation of photosynthetic products, and increase dry matter accumulation.

3. Effect of Deficit-Regulated Irrigation on Water Use Efficiency in Potato Cultivation

Water use efficiency (WUE) is a critical indicator of the economic utilization of water during the reproductive phase of crops. It is an essential metric for characterizing the level of water usage in irrigated agriculture and a reliable gauge for assessing the efficient use of water in agricultural crops [14,15]. Deficit-regulated irrigation has the potential to significantly enhance water use efficiency in potato crops. By precisely managing irrigation amounts, this method can substantially reduce transpiration rates, mitigate "luxury transpiration", decrease ineffective water consumption, and improve overall water utilization during crop growth. This strategy not only conserves water but also increases yield while meeting the potatoes' essential growth requirements. Research suggests that implementing moderate water deficit at different growth stages, especially during the tuber formation phase, can lead to notable improvements in water use efficiency. For example, applying a mild water deficit (RD1 treatment) during the tuber formation stage in green potatoes resulted in a slight yield reduction but significant enhancements in water use efficiency, irrigation water use efficiency, and harvest index. These metrics were found to

be 8.10%-41.57%, 3.57%-42.62%, and 10.16%-34.38% higher than other treatments and control conditions, respectively [16]. Experimental results showed that the lowest water use efficiency (WUE) of 4.42 kg/mm occurred in the high-water treatment throughout the potato lifecycle, while the medium-water treatment not only yielded higher outputs but also achieved a maximum WUE of 6.05 kg/mm. Therefore, moderate water stress during deficit-regulated irrigation improves water use efficiency. Experiments conducted in a large field using a rain shelter demonstrated that strategic reductions in irrigation during the seedling period significantly enhanced both potato yield and water use efficiency. Additionally, appropriate irrigation management during the tuber formation and expansion phases, combined with moderate water deficit during the starch accumulation period, proved effective. The results indicated a yield increase of 10.16% to 34.38% compared to other treatments and the control group. Appropriate water stress can effectively reduce water consumption and enhance water use efficiency in potato cultivation, but excessive water stress may reduce yield [17-19]. Therefore, determining the optimal level of water deficit is crucial for improving overall water use efficiency in deficit-regulated irrigation. Moderate water deficit treatment during the seedling stage and starch accumulation can enhance water use efficiency, but its application during tuber formation and expansion significantly reduces this efficiency. These findings highlight that while moderate water deficit treatment can improve water use efficiency and reduce overall water consumption, its timing plays a key role in optimizing these benefits [20].

4. Impact of Deficit-Regulated Irrigation on Potato Yields

The ultimate goal of deficit-regulated irrigation is to save water and increase yield. Water stress induces varying responses in potato yield. Experimental results showed that under mild water stress during the seedling stage, the yield decreased by 5.3% compared to the control group, with no significant difference observed. In contrast, during the stages of tuber formation, expansion, and starch accumulation, significant reductions of 16.43%, 31.05%, and 17.54% were observed, respectively, when compared to the control group. These findings suggest that timely and appropriate water stress levels may benefit yield enhancement. It has been demonstrated that a significant positive correlation exists between yield and field water holding capacity. When the field water holding capacity was below 85%, yield increased as field water holding capacity rose. However, when it exceeded 85%, yield started to decline. This indicates that moderate water deficit could be beneficial for yield. Observations showed that there was no significant difference in potato yield between water deficit treatment during the seedling stage and the control group. In contrast, other water deficit treatments resulted in significantly lower potato yields compared to the control. Potting experiments indicated that as the degree of water deficit increased, the single-plant yield of two potato varieties decreased, with reductions of 30.7%-87.2% for one variety and 9.1%-92.9% for the other, compared to the control group, demonstrating that the potato yield decreases as the degree of water deficit intensifies. Experiments in rainproof greenhouses showed that drought stress increased the number of small potatoes but reduced the number of large and medium-sized potatoes, thus lowering overall yield. Severe drought stress had the most significant effect on the composition of potato yield. Therefore, deficit-regulated irrigation for potatoes should focus on the right timing and appropriate water stress levels to minimize yield reduction or even enhance it, thereby achieving increased yield and improved water use efficiency.

5. Conclusion

As a water-saving and high-efficiency irrigation technology, deficit-regulated irrigation provides a scientific basis for cultivating potatoes in a water-efficient and high-yield manner, while also opening new opportunities for enhancing both potato yield and quality. By precisely controlling the timing and amount of irrigation water, deficit-regulated irrigation effectively improves photosynthetic efficiency during critical growth stages,

thereby boosting the plant's adaptability and resilience to water stress. This optimization leads to better accumulation and distribution of photosynthetically active products. The study further demonstrated that deficit-regulated irrigation indirectly enhances photosynthetic capacity by affecting various physiological parameters of potato leaves, such as photosynthetic rate, stomatal conductance, and transpiration rate. This improvement establishes a solid material foundation for tuber expansion. At the same time, the application of an appropriate deficit-regulated irrigation system significantly increased potato plant weight, tuber count, and overall yield, highlighting its potential in enhancing crop productivity.

Future research should explore the specific responses to deficit irrigation across different climatic conditions, soil types, and potato varieties. Furthermore, elucidating the molecular mechanisms underlying the impact of deficit irrigation on potato growth, development, yield, and quality is essential. This knowledge will provide vital scientific and technological support for the sustainable advancement of potato production.

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