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Effects of Water Regulation Deficit on Soil Environment, Yield and Water Use Efficiency of Potato

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Abstract: Proper and timely irrigation is essential for crop growth and yield formation. It enhances the soil's ecological environment, conserves resource, ensures consistent and high crop yields, and improves overall quality and efficiency. This paper reviews the impacts of water scarcity under drip irrigation on soil thermal and moisture conditions, soil enzyme activity, microbial populations, nutrient content, yield, and water use efficiency in potatoes. Additionally, it discusses existing challenges and potential future research directions, aiming to provide guidance for precise irrigation strategies and the cultivation of high-yield, high-quality potatoes.

Keywords: potato; water regulation deficit; water stress; soil nutrients; yield

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1. Introduction

Potato (Solanum tuberosum) is an annual herbaceous plant and ranks as the fourth most important staple food crop globally, following wheat, rice, and corn. It is a rich source of essential nutrients for humans, including protein, starch, amino acids, vitamins, and other vital compounds [1]. Given its critical role in food security, China, as both a major producer and consumer, has seen a continuous increase in potato cultivation, with the annual planting area surpassing 6 million hectares in recent years [2]. Potatoes are known to be relatively sensitive to water stress, characterized by shallow roots and a loose root structure. Severe water deficit can significantly hinder the growth and development of their roots, leaves, and tubers [3]. Since the 1970s, the increased frequency and intensity of droughts in various regions have posed challenges to the expansion of the potato industry in China [4]. Consequently, it has become crucial to develop effective water management strategies that not only enhance potato yields but also improve soil quality, optimize water usage, and increase economic returns.

2. Effects of Water Regulation Deficit on Soil Hydrothermal Characteristics

Soil water is a critical factor influencing crop growth, development, and metabolic activities throughout the entire growing period, as it impacts the rate, depth, and amount of soil nutrient movement [5]. The water needs of crops vary across different growth stages. During the early stages of growth, when plant roots are shallow and underdeveloped, the water demand is relatively low. Excessive irrigation during this period can result in excessive soil moisture, disrupting nutrient movement and hindering plant growth and development. This can significantly affect potato yield, including tuber weight, size, and overall yield [6]. Research has shown that the tuber expansion stage is particularly critical for dry matter accumulation in potatoes, and water shortages during this stage can lead to insufficient water supply, which may cause yield reductions. While slight water deficits may cause only a modest decrease in yield, water utilization efficiency and irrigation water use efficiency improve significantly, contributing to both water conservation and increased production [7].

Soil temperature plays a dual role in crop growth, influencing both root development and the dissolution of salts, as well as having a substantial effect on soil gas emissions [8]. Apart from atmospheric temperature, soil temperature is largely regulated by irrigation practices, and optimal irrigation management is key to maintaining suitable soil temperatures. Irrigation affects the microclimate of farmland soil, including its temperature, thereby influencing crop growth. Studies indicate that there is a significant interaction between irrigation practices and soil temperature [9]. When mulching methods remain constant, soil temperature tends to increase as irrigation rates decrease. This could be due to mulching reducing water evaporation, helping to regulate soil temperature and conserve moisture. The mulch film also shields the soil surface from direct exposure, causing the soil temperature to rise above atmospheric levels during the warming phase, with a delayed cooling effect during the cooling phase. Under deficit irrigation with mulch and drip irrigation systems, rainfall can be utilized efficiently to increase soil moisture, raise soil temperatures in various layers, and enhance the accumulated temperature during the potato growing period. This creates an optimal hydrothermal environment for root growth, promoting tuber germination, increasing dry matter accumulation, and improving water use efficiency [10,11].

3. Effects of Water Regulation Deficit on Soil Enzyme Activity and Microbial Community

Soil enzymes, often referred to as the "active reservoir of plant nutrient elements", play a vital role in the decomposition of organic matter, material circulation, and energy transformation in the soil. They are crucial in promoting plant nutrient absorption and metabolic processes, acting as dynamic catalysts in various biochemical reactions. The activity of soil enzymes serves as a key indicator for assessing soil quality and health [12,13]. Water serves as a catalyst for soil enzyme reactions. A moderate water deficit can help maintain optimal soil aeration, enhancing the rate of decomposition and mineralization of organic matter, and promoting the interaction between enzymes and their substrates. However, excessive water supply can lead to the deterioration of soil aeration, which negatively impacts the secretion and concentration of soil enzymes. This results in a dilution effect, reducing enzyme activity and inhibiting enzymatic reactions [14]. Research has shown that mild water stress can stimulate soil enzyme activity. For instance, as water deficit increases, the activities of soil urease and sucrase initially rise before declining, indicating that moderate water stress is beneficial for enhancing enzyme activity [15]. Additionally, studies have found that under consistent fertilizer application and a 20% water-saving treatment, soil enzyme activities, including catalase, sucrase, urease, and alkaline phosphatase, reach their maximum levels in the 0-20 cm soil layer. Excessive water supply, on the other hand, results in a decline in these enzyme activities [16].

Soil microorganisms are integral to the decomposition and conversion of plant nutrients, playing a pivotal role in the transformation of soil organic carbon and other nutrient elements. The presence and activity of these microorganisms are key indicators of soil fertility and environmental quality [17]. Soil water content has a significant impact on rhizosphere microorganisms. Drought conditions create osmotic stress, leading to the death and lysis of soil microorganisms [18]. However, studies have indicated that a moderate water deficit can enhance root activity and the root-to-shoot ratio of crops, improving the structure and diversity of rhizosphere microbial communities. This promotes nutrient cycling in the soil, thereby fostering potato growth [19]. Moreover, suitable water stress can influence the carbon assimilation process in plants via photosynthesis, which in turn affects the quality and quantity of carbon sources available to rhizosphere microorganisms [20]. It has been suggested that reasonable water management strategies, including slight water deficits, can foster the growth of microbial communities and improve hydrocarbon content in the soil.

4. Effects of Water Regulation Deficit on Soil Nutrient Content

Soil nutrients are essential for providing the necessary elements for crop growth, directly influencing plant development and forming the foundation for yield formation [21]. The concentration of soil nutrients typically decreases with soil depth. Potato roots are most developed in the 0-20 cm soil layer, where root and microbial activity is more intense, facilitating the accumulation and cycling of nutrients. As soil depth increases, the influence of soil structure diminishes, leading to a gradual reduction in nutrient content at deeper soil levels [22]. Irrigation plays a significant role in influencing soil organic matter content. Proper irrigation practices can enhance microbial activity, accelerate organic matter decomposition, and increase the availability of nutrients in the soil, thereby promoting nutrient absorption and utilization by plants. However, excessive irrigation can hinder microbial activity, increase nutrient leaching, and impede soil fertility improvement, ultimately limiting crop yield. Studies indicate that under deficit irrigation with drip systems and mulching, soil nutrient consumption follows this pattern: available potassium > alkali-hydrolyzed nitrogen > available phosphorus [23]. A mild water deficit during the seedling stage can help stimulate nutrient absorption by plants. However, as the potato progresses through its growth stages, its nutrient demands increase. If water deficit continues, soil moisture content decreases, obstructing nutrient absorption pathways for crops. As water stress intensifies, the absorption of available phosphorus and potassium becomes less efficient. Furthermore, severe water deficit has a lasting negative impact on soil nutrient absorption, and the yield may not recover even with subsequent rewatering treatments.

5. Effects of Water Regulation Deficit on Yield and Water Use Efficiency

Timely and appropriate water management is a crucial strategy for improving crop yield and optimizing water use efficiency [24]. A study investigated the effects of regulated deficit irrigation at different growth stages of potatoes [25]. The results showed that mild water deficit during the seedling stage did not lead to significant differences in yield compared to full irrigation, but both water use efficiency and irrigation water use efficiency reached their maximum. Additionally, the overall quality of the potatoes was notably improved. The study further concluded that each growth stage of potatoes is distinctly influenced by water management practices. Full irrigation throughout the entire growth period resulted in the highest yield, while water deficit during the tuber expansion stage had a considerable negative effect on potato yield. In contrast, a mild water deficit during the tuber formation stage led to a slight decrease in yield, but this reduction was less significant compared to other treatments, highlighting that moderate water stress can still maintain relatively high yields [26]. Furthermore, the maximum water use efficiency, irrigation water use efficiency, and harvest index were improved by 41.57%, 42.62%, and 34.38%, respectively. These results contributed to enhanced plant growth and development, better potato quality, increased nutritional value, and a higher commercial potato rate, achieving the combined goals of water conservation, quality improvement, and increased production [27].

6. Conclusion

Potatoes, being a low-input, high-yield, and dual-purpose crop in the arid regions of northwest China, traditionally rely on flood irrigation, which is highly water-intensive. Research has shown that appropriate water regulation deficit can have beneficial effects on potato growth and development, soil hydrothermal properties, soil enzyme activity, microbial communities, nutrient content, yield, and water use efficiency. These findings highlight the potential for significant water savings and efficiency improvements in potato cultivation. However, challenges remain, including difficulties in determining the optimal timing for deficit irrigation, unclear mechanisms of internal transformation, and a lack of interdisciplinary research across different fields. Therefore, it is essential to further investigate the water response mechanisms of potatoes and develop a more precise water deficit regulation model. This can be achieved by enhancing scientific research, optimizing irrigation strategies, improving soil monitoring, and upgrading equipment performance. Such efforts will promote the sustainable development and application of water deficit regulation technology under drip irrigation systems for potato cultivation. In doing so, more scientifically sound and practical irrigation guidelines can be established, supporting the healthy and sustainable development of agriculture.

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