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Effects of Water Deficit on Water and Nitrogen Coupling Management of Potato

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Abstract: This study aimed to explore how regulated water deficits influence potato growth, yield, and the efficiency of both water and nitrogen use under a water-nitrogen integrated management approach. A field experiment was designed to examine the interactive effects of water limitation and nitrogen application on soil moisture dynamics throughout the entire potato growing season. When soil moisture was maintained at 70-80% of field capacity (mild deficit), potato roots developed more vigorously, and despite a slight reduction in aboveground biomass, tuber yields remained comparable to those under full irrigation. A slightly more pronounced water deficit (60-70% of field capacity) further increased WUE, though a minor yield reduction was observed. In contrast, severe water stress (below 60% of field capacity) notably restricted plant growth and led to a substantial decline in yield. The study also found that increasing nitrogen input could partially mitigate the negative impacts of water shortage. However, applying nitrogen in excess not only reduced its utilization efficiency but also heightened environmental risks. These results provide important guidance for optimizing water and nitrogen management in potato cultivation. It is recommended that, in practical applications, a mild to moderate deficit irrigation strategy be employed, with nitrogen fertilizer rates adjusted in response to soil moisture levels to support both resource efficiency and sustainable potato production.

Keywords: potato; regulated water deficit; nitrogen management; water use efficiency; nitrogen use efficiency

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1. Introduction

Potatoes, ranked as the fourth most significant food crop worldwide, are essential for enhancing food security and fostering sustainable agricultural growth [1]. However, increasing global climate variability and worsening water scarcity have posed serious challenges. Enhancing potato yield and stability under limited water availability has thus become a central focus of contemporary agricultural research [2]. Regulated water deficit (RWD), recognized as an effective water-saving cultivation strategy, has been increasingly applied in crop management.

This study aimed to evaluate the impact of RWD on potato growth performance, yield outcomes, and the efficiency of water and fertilizer use within the framework of integrated water-nitrogen management. Through experimental treatments involving varying degrees of water deficit and nitrogen application, the research systematically assessed the effects of RWD on potato development, productivity, and quality. The findings contribute to the theoretical foundation for optimizing water and nutrient strategies, supporting the goal of achieving water-efficient and high-yield potato cultivation.

2. The Effect of Water Deficit on Physiological and Ecological Indicators of Potatoes

2.1. Plant Morphology

Regulated water deficit primarily influences the morphological characteristics of potato plants, particularly in root and shoot development [3]. Under conditions of mild water stress (70-80% of field capacity), potato roots exhibited enhanced growth, characterized by deeper and wider distribution patterns [4]. This improved root architecture enables the plants to access water and nutrients from deeper soil layers, thereby enhancing drought tolerance and overall resource use efficiency [5].

As water stress intensifies, shoot development becomes increasingly restricted. In a moderate deficit range (60-70% of field capacity), a slight reduction in plant height and leaf area index was observed, although the canopy structure remained relatively intact [6]. However, when soil moisture dropped below 60% of field capacity, plant growth was notably stunted, with symptoms such as leaf curling and thinner, weaker stems becoming apparent. These changes severely limit the plant's ability to conduct photosynthesis effectively [7].

2.2. Physiological Indexes

Water deficit exerts a considerable impact on the physiological metabolism of potato plants [8]. Under mild to moderate drought conditions, leaf stomatal conductance declines, leading to a suppression of transpiration [9]. This limitation on water loss contributes to enhanced water use efficiency. In addition, moderate water stress promotes the accumulation of osmoprotectants such as proline and soluble sugars, which strengthens cellular tolerance to stress conditions [10].

However, severe water stress results in a decline in chlorophyll content and a marked reduction in photosynthetic activity [11]. Although the activity of antioxidant enzymes increases under such stress, the overproduction of reactive oxygen species cannot be fully neutralized. This imbalance leads to intensified lipid peroxidation of cell membranes, ultimately impairing key physiological functions in the plant [12].

2.3. Growth Cycle

The regulation effect of water deficit strategy on potato growth cycle was significant [13]. Under mild water deficit, the vegetative growth period of potato was slightly shortened, while the tuber formation and expansion periods were relatively prolonged [14]. The adjustment of the growth cycle is beneficial to the transportation and accumulation of photosynthate to the tuber. This adjustment increases the economic yield by promoting the transport and accumulation of photosynthates in the tubers [15].

Moderate water deficit can further shorten the vegetative growth period, but it can also lead to early tuber formation. Excessive water deficit will significantly shorten the whole growth period, resulting in early maturity of tubers, which is not conducive to the formation of yield. Therefore, the reasonable water deficit regulation strategy should optimize the water supply in each growth stage on the basis of ensuring the normal growth and development of crops. To achieve the goal of efficient water saving and stable production [16].

3. Effects of Regulated Water Deficit on Yield and Quality of Potato

3.1. Production

The effect of regulated water deficit on potato yield showed obvious dose effect [17]. Under mild water deficit (70-80% of field capacity), the tuber yield of potato was equivalent to that of full irrigation. The tuber yield of potato was equivalent to that of full irrigation, or even showed a slight improvement. This was mainly due to the root development and preferential allocation of photosynthate to tubers induced by water stress.

A moderate water deficit (60-70% field capacity) may result in a small decrease in yield, but the decrease is usually not more than 10%. This yield loss is somewhat acceptable considering the significantly improved water use efficiency. However, when the water deficit was further increased (<60% of field capacity), the tuber yield decreased significantly. The decrease can reach more than 30%, which seriously affects the economic benefit [18].

3.2. Tuber Quality

The impact of controlled water deficit on potato tuber quality manifests in several ways. Moderate water stress enhances dry matter and starch content, which is crucial for processing potato varieties. Additionally, mild to moderate water limitations help reduce reducing sugar levels, thereby improving the processing quality of products like chips and fries.

However, excessive water deficit leads to an increase in tuber malformation and larger pericarp gaps, which negatively affect tuber marketability. Severe water shortages may also cause physiological issues such as brown heart and hollow tubers, further lowering quality. Therefore, achieving optimal tuber quality requires balancing moisture regulation with product standards [19].

3.3. Economic Traits

Water deficit regulation strategy had a significant effect on the economic traits of potato. Under mild to moderate water deficit, although the number of tubers per plant may be slightly reduced, the average tuber weight and the rate of large tubers tended to increase. The optimization of this block structure is conducive to improving the commodity and market value.

Moderate water deficit can improve water use efficiency and nitrogen use efficiency, and reduce production costs. However, excessive water deficit will lead to an increase in the proportion of small tubers and a decrease in the rate of commercial tubers, which will directly affect economic benefits. Therefore, in actual production, it is necessary to comprehensively consider yield, quality, and resource utilization efficiency, and select the best water deficit regulation strategy in order to achieve a win-win situation of economic and ecological benefits.

4. Effects of Regulated Water Deficit on Nitrogen Absorption and Utilization

4.1. Nitrogen Absorption Efficiency

The nitrogen uptake efficiency of potato was significantly affected by water deficit. Under mild water deficit (70-80% of field capacity), the nitrogen uptake efficiency of potato plants increased slightly. This may be due to the fact that moderate water stress promotes the growth and distribution of roots and increases the contact area between roots and soil, thereby improving the absorption capacity of nitrogen. However, as water deficit increased, nitrogen uptake efficiency declined. A moderate water deficit (60-70% of field capacity) led to a 10-15% decrease in nitrogen uptake efficiency, while a severe water deficit (<60% of field capacity) caused a more than 30% reduction in efficiency.

Water deficit not only directly affected the absorption activity of roots. It also indirectly affects the availability of nitrogen by changing the concentration and mobility of nitrogen in soil solution. Therefore, in the potato water and nitrogen coupling management. Maintaining a moderate soil moisture content is essential for effective nitrogen uptake [20].

4.2. Nitrogen Use Efficiency

The effect of regulated water deficit on nitrogen use efficiency of potato showed a complex nonlinear relationship. Under mild to moderate water deficit conditions, the nitrogen use efficiency increased. Specifically, a mild water deficit (70-80% of field capacity) increased nitrogen use efficiency by 5-10%, Moderate water deficit (60-70% of field capacity) increased nitrogen use efficiency by 10-15%. This phenomenon may be due to the promotion of nitrogen metabolism and redistribution in plants under moderate water stress. The utilization efficiency of nitrogen is improved [21].

When the degree of water deficit was further increased, the nitrogen use efficiency began to decrease significantly. Severe water deficit (<60% of field capacity) can result in a 20-30% reduction in nitrogen use efficiency. This was mainly due to the inhibition of photosynthesis and biomass accumulation under severe water stress. The assimilation capacity and transformation efficiency of nitrogen were reduced. Therefore, precise water management should be employed to maintain an appropriate water deficit in potato production by precise water management in potato production. To maximize nitrogen use efficiency [22].

4.3. Nitrogen Distribution in Plant

Water deficit significantly changed the distribution pattern of nitrogen in potato plants. Under mild water deficit (70-80% of field capacity), plants tended to allocate more nitrogen to roots and tubers, so as to enhance the water absorption capacity and promote the development of tubers. This allocation strategy is beneficial to improve the drought resistance and yield stability of crops. Moderate water deficit (60-70% of field capacity) further enhanced this trend. The proportion of nitrogen content in roots and tubers increased by 10-15%.

Severe water deficit (<60% of field capacity) can break this balance and lead to the imbalance of nitrogen distribution among plant organs. The nitrogen content in the leaves decreased significantly, which affected the photosynthetic efficiency. The nitrogen accumulation in tubers was also inhibited, which affected the final yield and quality. Therefore, in the coupling management of water and nitrogen in potato, it is necessary to optimize the distribution of nitrogen in the plant through reasonable water regulation. To achieve efficient utilization and balanced distribution.

5. Conclusion

This study examined how water deficit affects nitrogen uptake and utilization in potatoes, providing valuable insights for optimizing production management strategies. The results revealed that moderate water stress could significantly enhance nitrogen use efficiency and improve the distribution of nitrogen within the plant. Specifically, mild to moderate water deficit (60-80% of field capacity) promoted root growth, increased nitrogen uptake efficiency, and optimized nitrogen allocation to roots and tubers. However, severe water stress (<60% of field capacity) severely reduced nitrogen uptake and efficiency, leading to imbalanced nitrogen distribution. These findings underscore the critical role of precise water management in potato cultivation and offer guidance for nitrogen fertilizer application strategies. Future research should further investigate the interaction between controlled water deficit and nitrogen application rates, as well as the varying effects of water regulation on nitrogen absorption and utilization at different growth stages. This will provide a foundation for improving and implementing integrated water and nitrogen management technologies for potatoes. In practical applications, water and nitrogen management plans should be tailored to soil types, climate conditions, and specific potato varieties to achieve both resource efficiency and sustainable production.

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