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Research Progress on Effects of Water and Nitrogen Regulation on Yield and Quality of Potato

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Abstract: As the fourth most important food crop globally, potatoes play a crucial role in contributing to global food security. Enhancing both yield and quality is therefore of considerable importance. Among the many agronomic factors influencing potato development and productivity, water and nitrogen management has emerged as a central area of focus in recent research worldwide. This paper synthesizes recent advances related to water and nitrogen regulation in potato cultivation, particularly regarding their impacts on nitrogen accumulation, yield performance, quality attributes, and the efficiency of water and nitrogen utilization. Through a comprehensive evaluation of current findings, this study aims to offer a theoretical foundation for optimizing water and nitrogen use, thereby promoting simultaneous improvements in potato yield and quality.

Keywords: potato; water and nitrogen regulation; yield; quality; water and fertilizer utilization efficiency

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1. Introduction

Potato (Solanum tuberosum L.) is ranked alongside corn, wheat, and rice as one of the four principal food crops globally. Known for its rich nutritional content, high yield, stability, and strong adaptability, it enjoys widespread popularity [1]. In China, major potato-producing regions include Northeast China, Inner Mongolia, North China, and Yunnan-Guizhou, which feature cold to cool climates ideal for potato cultivation. Potatoes exhibit a broad range of soil adaptability, with shallow roots and loose structures. Light soil is considered most suitable for their growth. Potatoes are highly sensitive to water, requiring substantial water throughout their growth stages, particularly during tuber development, to ensure normal growth [2].

Nitrogen application is another key factor influencing potato production. Given nitrogen's essential role in plant growth and yield formation, studies indicate that proper nitrogen application supports efficient carbon assimilation through photosynthesis and promotes the accumulation and transport of dry matter [3]. Plant morphology, hydraulic properties, and photosynthetic physiological responses are key indicators of crops' reactions to stress. Drought or nitrogen deficiency in the early root zone can disrupt the balance between water supply and atmospheric evaporation demand [4]. Water and nitrogen

management refers to the strategic regulation of water and nitrogen inputs during different growth phases of the crop. By optimizing this coordination, water and fertilizer wastage can be minimized, leading to higher yield and improved quality [5].

China currently faces challenges such as a large population and a gradual reduction in arable land. While staple grain production is substantial, the country also imports significant amounts of grain. Strict control over food security is necessary to ensure sustainable growth, relying on the existing grain output [6]. Therefore, research into effective water and nitrogen control mechanisms for potatoes is essential for realizing efficient utilization of these resources.

2. Rule of Potato Water and Fertilizer Requirement

The distribution of freshwater resources in China is uneven, with significant seasonal variations, placing considerable constraints on agricultural production. This challenge is particularly evident in the inland northwest, where freshwater scarcity has emerged as a major limiting factor for agricultural development [7]. Crop water physiology is a complex process, as plants rely on water absorbed by their roots to sustain normal physiological functions in both above-ground and below-ground parts [8]. Effective irrigation systems not only enhance grower profitability but also help prevent ecosystem degradation, thereby supporting sustainable agricultural practices. Given their shallow root system and high sensitivity to water, potatoes require careful irrigation management to maintain both yield and quality [9]. A scientifically designed and properly executed irrigation strategy is essential for understanding the water demand patterns of potatoes and ensuring optimal growth conditions [10].

Research has shown that the water budget curve for potatoes during the growing season follows a "hollow" pattern [11]. Early-season water availability promotes seedling emergence and initial growth; however, as the crop matures, water consumption intensifies, depleting early moisture reserves. This shifts the water balance from surplus to deficit during mid-growth stages. With the onset of summer rainfall, water demand decreases, restoring the water balance and eventually leading to a surplus at maturity, thereby improving soil moisture conditions [11].

Studies also indicate that the tuber swelling phase represents the period of highest water demand, accounting for 40% to 45% of the total water consumption throughout the growing cycle [12]. Additional findings on spring-planted potatoes reveal that the tuber expansion phase consumes approximately 58.0% of total water usage during the growth period [13].

Water shortage during the tuber swelling phase has been shown to have the most detrimental effects on potato growth, significantly reducing biomass, leaf area index, tuber yield, and water use efficiency (WUE) [14]. In contrast, a slight water deficit during the starch accumulation phase may enhance the yield of commercial-grade potatoes. Water demand patterns and volumes for potatoes vary by region, influenced by geographical, climatic, and soil-related factors. Nevertheless, the overall trend throughout the growth cycle typically involves an increase in water demand during the early and mid-growth stages, followed by a gradual decline. The tuber expansion phase represents the period of highest water demand and intensity, making it critical to ensure adequate irrigation to support optimal development and maximize yield.

Chemical fertilizer use in agriculture must comply with agronomic guidelines to prevent soil degradation and environmental harm. In certain areas, excessive fertilizer application has led to the rapid depletion of soil nutrients, undermining fertility and threatening the sustainability of agricultural systems. This not only increases production costs but also endangers the stability of food supply. To promote sustainable agriculture, it is essential to address the root causes of fertilizer misuse and implement scientifically informed fertilization strategies that align with broader social development goals. As a high-

yield crop, potatoes are particularly sensitive to fertilization practices [15]. Proper fertilization enhances yield, improves quality, and reduces input costs.

Potato plants have dynamic nutrient requirements across different growth stages, particularly for nitrogen, phosphorus, and potassium. These nutrients must be supplied in appropriate ratios and at optimal times to ensure healthy growth and productive output. During the seedling stage, nutrient uptake primarily relies on the seed tuber, making seed quality a key determinant of early development. As growth progresses, nutrient demand increases, especially during the tuber formation and expansion stages. Although the tuber expansion stage demands large quantities of nutrients, the absorption rate slows compared to earlier phases. In the maturity stage, overall nutrient needs decline, but the redistribution of nutrients from leaves and stems to tubers becomes crucial for starch accumulation and final yield formation. Nitrogen, in particular, plays a vital role in leaf development [6]. Insufficient nitrogen can result in stunted growth and reduced canopy development, leading to significant yield losses. Conversely, excessive nitrogen — especially during the vegetative stage — can promote overgrowth of above-ground biomass at the expense of tuber development.

3. Effect of Water and Nitrogen Regulation on Potato Quality and Yield

The three primary nutrients essential for potato growth are potassium, nitrogen, and phosphorus, with potassium being the most critical, followed by nitrogen, and phosphorus being relatively less significant. An excess of nitrogen can promote excessive vegetative growth, redirecting energy toward stems and leaves and thus inhibiting tuber development and delaying physiological maturity. Potato yield is influenced by various factors, including cultivar type, planting date, soil texture, pH level, and moisture availability. Among these, the interaction between water and nitrogen is particularly important, as it significantly affects plant growth and physiological processes, especially within the root system. Nitrogen application can enhance root water use efficiency, while sufficient water availability supports nutrient uptake. An integrated approach to water and fertilizer management — ensuring timely and localized delivery of both inputs to the root zone — can reduce resource waste and improve utilization efficiency [3].

Potato quality is commonly evaluated based on parameters such as soluble sugar content, protein levels, and starch accumulation in the tubers. Optimizing water and nitrogen management has been shown to enhance nitrogen uptake and improve these quality indicators [11]. The application of conditioning agents in conjunction with traditional irrigation and fertilization practices further improves nitrogen absorption, thereby contributing to better tuber quality. Balanced water and nitrogen supply also promotes greater plant height, larger leaf area, and increased dry matter accumulation. However, both excess and deficiency of water or nitrogen can adversely affect plant development. Over-irrigation may impair soil aeration, restricting root respiration and nutrient absorption, while excessive nitrogen can stimulate vegetative overgrowth and reduce the efficiency of photosynthetic energy utilization.

In general, potato yield responds to changes in irrigation and nitrogen application in a non-linear pattern. Yield tends to increase with rising nitrogen or irrigation levels up to an optimal threshold, beyond which further increases result in yield decline. Moderate levels of both irrigation and fertilization are often associated with the highest yield, nutrient use efficiency, and economic return. Moreover, increasing nitrogen levels under stable water conditions can improve tuber weight, marketable yield, starch content, and nutritional quality, such as vitamin C concentration. However, when nitrogen exceeds optimal levels, both yield and quality may suffer. The coupling effect of water and nitrogen remains a central focus in potato cultivation research, as balanced management of these two inputs is essential for maximizing productivity and sustaining crop quality.

4. The Impact of Water and Nitrogen Regulation on the Utilization Efficiency of Water and Nitrogen in Potatoes Has Been Studied

The efficiency of crop water and nitrogen utilization is a key indicator of agricultural productivity, directly affecting both yield and quality, as well as the ecological footprint of farming practices. Enhancing the use efficiency of these resources not only boosts crop performance but also mitigates environmental degradation, supporting the sustainable development of agriculture. Studies have shown that water use efficiency tends to increase with nitrogen input up to an optimal level, after which further application leads to a decline [1]. Excessive nitrogen in the soil can interfere with plant water uptake, ultimately reducing water use efficiency. Under conditions of limited irrigation, increasing nitrogen input may help compensate for water deficiency, while in high-irrigation scenarios, additional water can offset insufficient nitrogen [13]. Similarly, under drought stress, increased nitrogen may improve crop yield and water use efficiency, although it may also reduce nitrogen fertilizer efficiency. After adequate irrigation, moderate nitrogen application further enhances yield, while over-application proves detrimental [14].

Variations in nitrogen use efficiency among potato varieties have been observed, with some varieties directing more nitrogen toward tuber formation, thereby improving overall water and nutrient use efficiency. Nitrogen-efficient varieties typically achieve higher tuber nitrogen concentrations with lower uptake, while nitrogen-inefficient varieties absorb more nitrogen but exhibit lower tuber accumulation. Moreover, when water supply is limited, increasing nitrogen does not necessarily lead to higher nitrogen productivity, and excessive inputs of either water or nitrogen can reduce overall efficiency. When nitrogen application is held constant, nitrogen productivity increases with moderate water input but declines when irrigation exceeds optimal levels.

Soil moisture distribution is also influenced by water and fertilizer management practices. The optimal soil layer for potato tuber development is between 10 and 30 cm, where moisture tends to accumulate. With increased irrigation and fertilization, nutrients are often leached deeper into the soil profile. Throughout the potato growth cycle, water consumption displays a parabolic trend, initially decreasing and then increasing with irrigation intensity, while generally rising with increased fertilization. These dynamics underscore the importance of coordinated water and nutrient management to achieve both high yield and environmental sustainability.

5. Conclusion

Recent research on water and nitrogen management in potato cultivation highlights that implementing effective water and nitrogen regulation strategies can significantly boost both yield and quality. These practices also improve soil health, reduce the risk of diseases and pests, and support sustainable potato production. Moving forward, further research on the interactions between water and nitrogen is essential, alongside the development of precise management strategies, effective disease and pest control measures, and sustainable production practices. This will provide more scientific and efficient support for potato farming. In China's inland arid areas, where the climate is dry and soil quality is poor, water and nitrogen have become key limiting factors for crop growth and yield under the influence of global warming. Ensuring adequate water and nitrogen supply is critical for enhancing crop yields and optimizing resource efficiency.

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