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# Nitrogen use efficiency and its impact on yield and tuber development in potato (*Solanum tuberosum* L.) genotypes: Review

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## Abstract
Nitrogen use efficiency (NUE) is a crucial determinant of sustainable agricultural practices, particularly in potato (*Solanum tuberosum* L.) production, where it significantly impacts yield, environmental sustainability and farm profitability. NUE consists of two primary components: nitrogen uptake efficiency (NUE uptake), which refers to the plant's capacity to absorb nitrogen from the soil and nitrogen utilization efficiency (NUE utilization), which is the effectiveness of converting absorbed nitrogen into crop biomass or tuber yield. While nitrogen is essential for optimal potato growth, inefficient nitrogen use leads to environmental problems such as nitrogen leaching, greenhouse gas emissions and soil degradation. This results in both economic losses and environmental harm. As nitrogen fertilizer costs rise, improving NUE is vital to reduce dependence on chemical fertilizers and enhance the environmental sustainability of potato farming. Various factors influence NUE, including genetic variation, environmental conditions and agronomic practices like fertilization methods, irrigation strategies and soil management techniques. Recent advancements in breeding for NUE and the integration of precision agriculture technologies, such as variable-rate fertilization and real-time monitoring systems, have demonstrated significant potential in optimizing nitrogen management. Additionally, strategies like integrated nutrient management, using organic amendments and incorporating biofertilizers have been found to improve nitrogen uptake and reduce nitrogen losses from the system. However, achieving high NUE in potatoes requires a holistic approach, encompassing improved plant breeding, better understanding of plant-soil-environment interactions and precision agronomy practices. This review explores the factors influencing NUE in potatoes, the challenges faced in optimizing nitrogen management and the promising opportunities for improvement through genetic advancements and modern agricultural technologies. By adopting integrated approaches, the potato industry can move towards more sustainable, efficient and profitable production, thus contributing to global food security and environmental conservation.

**Keywords:** Nitrogen use efficiency, biofertilizers, sustainable agriculture, nitrogen uptake efficiency, genetic improvement, integrated nutrient management

## Introduction
Potato is one of the world's most important food crops, grown in diverse climates and soils. As a high-input crop, it is heavily reliant on nitrogen for optimal growth and yield. However, the use of nitrogen fertilizers has raised concerns due to its environmental impact, including nitrogen runoff, leaching and greenhouse gas emissions. Thus, enhancing nitrogen use efficiency (NUE) is crucial for both increasing productivity and mitigating environmental harm. Nitrogen (N) is one of the most critical macronutrients for plant growth, influencing essential physiological processes such as photosynthesis, protein synthesis and the overall productivity of crops. Potatoes (*Solanum tuberosum* L.) are a highly nitrogen-demanding crop and efficient nitrogen use is central to achieving high yields while minimizing environmental and economic costs. Nitrogen Use Efficiency (NUE) refers to the ratio of crop yield to the amount of nitrogen applied and improving NUE is essential for sustainable agricultural practices (Hirel *et al*., 2020) [10]. Despite its importance, nitrogen management in potato cultivation remains a complex challenge, with the need to balance high productivity with reduced nitrogen losses to the environment.

**Objective and Scope**

The primary objective of this paper is to provide a comprehensive review of current knowledge surrounding Nitrogen Use Efficiency (NUE) in potato (*Solanum tuberosum* L.) cultivation. Given the crop's global economic importance and the increasing need for sustainable agricultural practices, improving NUE in potatoes is a critical area of research. This review synthesizes findings from recent studies and offers an integrative perspective on the genetic, agronomic and environmental factors that influence nitrogen uptake, assimilation and utilization in potato plants.

**Role of Nitrogen in Potato Growth and Tuber Development**

Nitrogen plays a pivotal role in potato physiology, beginning with the early vegetative phase where it enhances leaf area, chlorophyll synthesis and overall canopy development. A robust canopy is critical for intercepting solar radiation, which directly influences photosynthesis and assimilate production. As the crop transitions into tuber initiation and bulking, nitrogen facilitates the translocation of assimilates from leaves to developing tubers (Zhang *et al*., 2022) [32]. However, the timing and quantity of nitrogen are crucial excessive nitrogen early in the growing season can delay tuber initiation, reduce dry matter accumulation in tubers and promote excessive vegetative growth (Tiwari *et al*., 2021) [23]. Nitrogen deficiency results in stunted growth, chlorosis and reduced tuber set and size. Moreover, nitrogen significantly affects the partitioning of biomass between foliage and tubers. High nitrogen levels promote shoot biomass at the expense of tuber development if not balanced with appropriate management practices (Li *et al*., 2024) [15]. The Harvest Index (HI), which represents the proportion of total biomass allocated to tubers, can decline under both deficient and excessive nitrogen conditions.

Research shows that NUE influences both the number and size of tubers, which are primary yield components in potato. For instance, cultivars with better root development and higher nitrogen assimilation capacity tend to perform better under limited nitrogen availability (Tiwari *et al*., 2021) [23]. Therefore, understanding nitrogen dynamics in potatoes and how it influences growth phases is essential to optimize yield and quality while avoiding unnecessary nutrient losses.

**Strategies to Improve Nitrogen Use Efficiency**

Improving NUE in potato involves a combination of genetic, agronomic and technological approaches. One of the primary strategies includes the adoption of site-specific nitrogen management through tools like soil testing, leaf nitrogen sensors and crop growth models to apply the right amount of nitrogen at the right time. Precision farming techniques such as variable rate application have shown significant improvements in NUE by targeting nitrogen applications based on in-field variability (Zhang *et al*., 2022) [32]. Split nitrogen applications and controlled-release fertilizers can align nitrogen availability with crop demand, reducing leaching and volatilization losses. Recent studies also show that integrating organic manures with inorganic fertilizers known as Integrated Nutrient Management (INM) enhances NUE by improving soil microbial activity and nitrogen mineralization (Thakur *et al*., 2023) [22]. From a breeding perspective, the development of potato cultivars with improved root systems, higher nitrogen uptake efficiency and better sink strength for tuber filling is crucial. Marker-assisted selection and genomic tools are increasingly being used to identify traits associated with high NUE (Wang *et al*., 2023) [26]. Efficient irrigation methods, particularly drip irrigation, have also been linked with improved NUE by maintaining consistent soil moisture, thereby enhancing nutrient solubility and uptake. Drip fertigation (a combination of irrigation and fertilization) has been shown to increase both water and nitrogen use efficiency in potatoes (Wang *et al*., 2022) [24].

**Main Components of Nitrogen Use Efficiency (NUE) in Potato**

Nitrogen Use Efficiency (NUE) in potato is a critical aspect of optimizing crop yield while minimizing environmental impact. NUE in potatoes can be broken down into several key components. These components help assess how effectively the plant uses nitrogen (N) applied through fertilizers or naturally available in the soil. Various components of NUE described below:

**1. Nitrogen Uptake Efficiency (NUpE)**

Nitrogen Uptake Efficiency refers to the ability of the potato plant to extract nitrogen from the soil. This efficiency is influenced by the root systems architecture, soil nitrogen availability, microbial activity and the timing and placement of nitrogen fertilizer. Potatoes typically have a relatively shallow root system, which can limit nitrogen uptake, especially in dry or compacted soils. Enhancing NUpE involves optimizing root health, selecting cultivars with improved root traits and using practices such as split nitrogen applications to ensure availability when the plant needs it most. In essence, NUpE determines how much of the available nitrogen the plant is actually able to absorb and use for growth (Zhang and Wang 2023) [29]

$$\text{NUpE} = \frac{\text{Total N in Plant biomass}}{\text{Total N applied (or avilable)in soil}}$$

**2. Nitrogen Utilization Efficiency (NUtE)**

Nitrogen Utilization Efficiency describes how effectively the plant converts the absorbed nitrogen into biomass or, more specifically for potatoes, into tubers. This component is influenced by the plant's internal nitrogen metabolism and its ability to allocate nitrogen efficiently to growing tissues, especially tubers (Zhang *et al*., 2024) [15]. A high NUtE means that the nitrogen absorbed by the plant contributes effectively to yield formation. Environmental conditions such as temperature, light and water availability, as well as genetic factors, significantly affect NUtE. Even if a plant absorbs a lot of nitrogen (high NUpE), poor utilization will lead to inefficient conversion into yield.

$$\text{NUtE} = \frac{\text{Total dry matter or tuber yeild}}{\text{Total N in plant biomass}}$$

**3. Agronomic Efficiency of Nitrogen (AEN)**

Agronomic Efficiency represents the increase in yield obtained per unit of nitrogen applied. This is a practical and widely used measure for assessing the economic return of nitrogen fertilization. It takes into account not just uptake and utilization but the overall yield response to applied nitrogen. For potato farmers, AEN is a critical indicator, as it reflects the direct benefit of nitrogen application in terms of tuber yield. A high AEN suggests that nitrogen application is well-justified and effectively enhances productivity. It is highly variable depending on soil fertility, weather and crop management practices (Ali *et al*., 2023) [1].

$$AEN = \frac{\text{Yield fertilized} - \text{Yield unfertilized}}{\text{Amount of N applied}}$$

**4. Partial Factor Productivity of Nitrogen (PFPN)**

PFPN is a broad measure of productivity per unit of nitrogen applied, calculated as the total yield divided by the total nitrogen input. While it doesn't separate the effects of uptake and utilization, it serves as a useful indicator at the field or farm level. PFPN is especially valuable when comparing different nitrogen management practices over time. A high PFPN indicates that the crop is producing a large amount of yield for each kilogram of nitrogen applied, suggesting efficient use of resources. However, it doesn't differentiate between yield increases from soil nitrogen reserves and applied nitrogen, so it must be interpreted with care (Yang *et al*., 2023) [28].

$$NPFPN = \frac{\text{Tuber yield}}{\text{Amount of N applied}}$$

**5. Nitrogen Recovery Efficiency (NRE)**

Nitrogen Recovery Efficiency measures the proportion of applied nitrogen that is actually recovered in the plant tissues, particularly aboveground biomass or tubers. It helps quantify how much of the nitrogen added through fertilizer is utilized by the crop versus how much is lost to the environment. High NRE values suggest that the crop system is effectively capturing the added nitrogen, thereby minimizing losses through leaching, volatilization, or denitrification. Low NRE is a sign of inefficiency and potential environmental risk, especially in sandy soils or under heavy rainfall conditions where nitrogen leaching is common.

$$NRE = \frac{\text{N uptake in fertilzed plot} - \text{N uptake in unfertilized plot}}{\text{N applied}} \times 100$$

NUE is calculated for identification of which variety is most efficient to estimate ability to give reasonable yield under marginal nitrogen content of soil. It helps also for declining cost of production to improve farm profit and to reduce environmental pollution (Powell *et al*., 2010) [18].

**6. Physiological Efficiency of Nitrogen (PEN)**

Physiological Efficiency refers to the yield increase obtained for each additional unit of nitrogen taken up by the plant. It reflects the internal use of nitrogen once it has been absorbed, essentially measuring how efficiently the plant converts nitrogen into economic yield (tubers). PEN depends on the balance between vegetative growth and tuber formation (Wang *et al*., 2024) [25]. High vegetative growth with limited tuber production may indicate poor PEN, even if nitrogen uptake is high. Selecting potato varieties with strong sink strength (tuber development) and managing nutrients to avoid excessive foliage can help improve PEN.

$$PEN = \frac{\text{Yield fertilized} - \text{Yield unfertilized}}{\text{N uptake fertiloized} - \text{N uptake unfertilized}}$$

**Factors Influencing Nitrogen Use Efficiency in Potato**

Several interrelated factors influence NUE in potatoes, including genetic, agronomic, environmental and soil-based variables. Genetic variability among potato cultivars significantly impacts nitrogen uptake, assimilation and translocation. Some varieties exhibit a higher NUE due to more efficient root systems or better photosynthetic nitrogen-use efficiency (PNUE), enabling them to convert nitrogen into biomass more effectively (Tiwari *et al*., 2021) [23]. Soil characteristics such as organic matter content, pH, texture and microbial activity influence nitrogen availability and transformation. For instance, sandy soils are more prone to leaching, which reduces nitrogen availability to plants, while clay-rich soils may enhance nitrogen retention but hinder aeration (Zhang *et al*., 2020) [32]. Additionally, soil pH affects nitrification and ammonification processes that regulate nitrogen forms available to plants. Agronomic practices like fertilizer timing, rate and application method play a vital role. Split nitrogen applications, where nitrogen is applied in multiple doses synchronized with the plant's demand, have been shown to significantly improve NUE compared to single large applications (Jiang *et al*., 2022) [12]. Similarly, fertigation (delivering nutrients through irrigation) can enhance uniform nitrogen distribution and uptake.

Environmental factors such as temperature, rainfall and solar radiation also affect nitrogen metabolism. High temperatures combined with nitrogen surplus can delay tuberization and increase the risk of disease and physiological disorders (Li *et al*., 2024) [15]. Water availability is another major factor, as nitrogen uptake is water-dependent; hence, proper irrigation is essential to avoid both nutrient stress and losses.

**Importance of NUE in Sustainable Potato Farming**

Sustainable farming practices strive to balance agricultural productivity with environmental stewardship. In the context of potato farming, improving Nitrogen Use Efficiency (NUE) plays a critical role in achieving these goals. As nitrogen is one of the most essential nutrients for crop growth, its effective use is key to optimizing both economic returns and environmental sustainability.

**1. Environmental Benefits of Improving NUE**

One of the primary environmental benefits of improving NUE in potato farming is the reduction in nitrogen-related pollution. Excess nitrogen application leads to leaching, runoff and volatilization, which can cause significant environmental problems, such as eutrophication in water bodies. When excess nitrogen enters aquatic systems, it promotes the growth of algae, leading to oxygen depletion, fish kills and the degradation of aquatic ecosystems. By enhancing NUE, farmers can reduce the amount of nitrogen lost to the environment, thereby mitigating the risk of water contamination and the adverse effects of eutrophication.

In addition to water pollution, nitrogen fertilizers are also a major source of greenhouse gas emissions, particularly nitrous oxide ($N_2O$). Nitrous oxide is a potent greenhouse gas with a global warming potential nearly 300 times greater than carbon dioxide. High NUE helps minimize the need for excessive nitrogen inputs, thereby reducing the production of nitrous oxide through microbial denitrification in the soil. This contributes to lowering the carbon footprint of potato farming and helps combat climate change.

**2. Soil Health and Fertilizer Efficiency**

Improving NUE also has significant benefits for soil health. Excessive nitrogen inputs can lead to soil acidification, which negatively affects soil structure, microbial activity and nutrient availability. By optimizing nitrogen management and enhancing NUE, farmers can maintain better soil conditions, reduce the risk of soil degradation and improve the long-term sustainability of potato production systems. High NUE encourages the efficient use of applied nitrogen, meaning less nitrogen is required to achieve high yields and less nitrogen is left to accumulate in the soil, thus reducing soil nutrient imbalances.

**3. Economic Benefits for Farmers**

From an economic perspective, improving NUE enables farmers to achieve optimal potato yields while reducing their dependence on nitrogen fertilizers. Fertilizer costs are a significant portion of production expenses in potato farming. By increasing NUE, farmers can lower their nitrogen input costs while maintaining or even increasing crop yields. This efficiency not only improves the profitability of potato farming but also reduces the financial risks associated with fluctuating fertilizer prices. Additionally, reducing nitrogen application leads to lower environmental compliance costs and less need for environmental remediation efforts.

**4. Integrating NUE into Sustainable Farming Practices**

The integration of NUE improvement into sustainable potato farming requires a holistic approach, combining improved agronomic practices with advances in breeding, soil management and precision agriculture. Practices such as split fertilization, the use of slow-release fertilizers and crop rotation can help optimize nitrogen availability to potatoes, ensuring that the plants use nitrogen most efficiently. In addition, breeding efforts focused on developing potato varieties with higher NUE will allow farmers to further reduce their reliance on nitrogen inputs while maintaining high productivity levels. Overall, improving NUE in potato farming is a fundamental component of sustainable agricultural systems. It enables farmers to increase productivity with fewer environmental and economic costs, contributing to more sustainable and resilient food systems in the face of growing global challenges such as population growth, climate change and environmental degradation.

**Factors responsible for Nitrogen Use Efficiency in tuber yield and biomass production**

Nitrogen use efficiency (NUE) is a critical determinant of potato yield and environmental sustainability. Several factors influence how effectively a potato crop utilizes the applied nitrogen, with both intrinsic plant characteristics and external environmental conditions playing key roles. Understanding these factors is essential for optimizing nitrogen management practices and maximizing potato production. Below are the primary factors affecting nitrogen use efficiency in potato crop.

**1. Genetic Factors**

The genetic makeup of potato varieties has a significant impact on their nitrogen use efficiency. Different potato cultivars exhibit varying abilities to absorb, utilize and translocate nitrogen. Genetic variation in root architecture, nitrogen uptake mechanisms and plant metabolism can result in significant differences in NUE. Breeding efforts focused on selecting varieties with enhanced nitrogen efficiency can help improve crop performance and reduce the need for excessive nitrogen fertilization (Moll *et al*., 1982) [17].

**2. Soil Fertility and Nitrogen Availability**

The availability of nitrogen in the soil, both from natural sources and fertilizers, directly influences NUE. Soils with low nitrogen levels often require higher nitrogen inputs to achieve desired yields, while excessive nitrogen in the soil can lead to nutrient imbalances and decreased nitrogen use efficiency. Proper soil management, including the use of organic amendments and precision fertilization, is essential for optimizing nitrogen availability and uptake (Battilani *et al*., 2008) [3].

**3. Timing and Method of Nitrogen Application**

The timing and method of nitrogen application play a crucial role in determining nitrogen uptake efficiency. Nitrogen applied at the wrong growth stage can lead to inefficient use and reduced yield. Split applications, where nitrogen is applied in stages throughout the growing season, can ensure that the crop receives nitrogen at the critical stages of development. Additionally, the application method whether through fertigation, foliar sprays, or soil incorporation can influence nitrogen absorption and utilization by the plant (Dong *et al*., 2010) [6].

**4. Environmental Factors**

Environmental conditions such as temperature, precipitation and humidity can affect nitrogen uptake and utilization. For example, nitrogen absorption is often higher during warm, moist conditions when plants are actively growing. Extreme weather events like drought or heavy rainfall can lead to nitrogen leaching or volatilization, reducing nitrogen availability to the plant and thus impacting NUE. Managing environmental stress through irrigation and other cultural practices is critical for maintaining high nitrogen use efficiency (Tanaka *et al*., 1984) [20].

**5. Root System and Soil Interactions**

The root system's efficiency in absorbing nitrogen plays a central role in NUE. A deep and extensive root system allows for better nitrogen uptake from the soil, especially in deeper soil layers where nitrogen might be less available. Additionally, interactions between the plant roots and soil microorganisms, such as nitrogen-fixing bacteria, can enhance nitrogen availability and uptake. Soil health, including microbial diversity, also contributes to better nutrient cycling and more efficient nitrogen utilization (Ishizuka, 1980) [11].

**6. Water Availability**

Water availability significantly affects nitrogen uptake. Under water stress conditions, the plant's ability to absorb and utilize nitrogen can be hindered, reducing NUE. Adequate irrigation ensures that the plant has access to water and nutrients, promoting optimal nitrogen uptake and assimilation. Additionally, excessive irrigation can lead to nitrogen leaching, reducing its availability to plants and decreasing NUE (Kumar *et al*., 2007) [13].

**7. Crop Management Practices**

Effective crop management practices, such as proper tillage, pest control and weed management, indirectly affect NUE. For example, weeds compete with the potato crop for both nitrogen and water, reducing nitrogen use efficiency. Similarly, pests and diseases can stress the plant and reduce its ability to efficiently use available nitrogen. Implementing integrated pest management (IPM) and other best practices ensures that the crop has the optimal environment for nitrogen uptake and utilization (Powell *et al*., 2010) [18].

**8. Fertilizer Type and Composition**

The type of nitrogen fertilizer used also impacts NUE. Different forms of nitrogen (e.g., ammonium, nitrate and urea) have varying rates of absorption and utilization by potato plants. Slow-release fertilizers or controlled-release formulations can provide a more consistent nitrogen supply, reducing losses and enhancing NUE. Additionally, using a balanced fertilizer that provides other essential nutrients alongside nitrogen can support overall plant health and improve nitrogen utilization efficiency (Lehrsch *et al*., 2000) [14].

## Challenges and Opportunities in Improving Nitrogen Use Efficiency

Although considerable progress has been achieved in understanding nitrogen use efficiency (NUE) in potato production systems, several challenges still hinder its full optimization. One major challenge lies in the inherently complex interaction between genetic traits, soil characteristics, climatic conditions and crop management practices. This complexity makes it difficult to create a one-size-fits-all recommendation for nitrogen application, particularly in diverse agro-ecological zones. Another persistent issue is the low nitrogen recovery rate in potato crops compared to cereals. Potatoes generally have shallow root systems, which makes them less efficient in nitrogen uptake, particularly when nitrogen is applied deep in the soil or lost to leaching. Furthermore, the application of excessive nitrogen, often seen in conventional farming practices, contributes to low NUE, economic inefficiency and increased risk of environmental degradation through nitrate leaching and nitrous oxide emissions (Powell *et al*., 2010) [18]. The variability in farmers' knowledge and access to resources further complicates the implementation of optimized nitrogen management strategies. Smallholder farmers, especially in developing countries, often lack access to precision technologies, decision-support systems, or soil testing services needed for site-specific nitrogen recommendations. Despite these challenges, there are promising opportunities to improve NUE in potatoes. Advances in genomics and marker-assisted breeding offer potential to develop potato varieties with improved nitrogen uptake and utilization capacities. Similarly, precision agriculture technologies, such as remote sensing, GPS-guided machinery and variable rate fertilization, provide tools to apply nitrogen more efficiently, both spatially and temporally.

## Conclusion and Future Perspectives on Nitrogen Use Efficiency

Improving nitrogen use efficiency in potato cultivation is a pressing need in the context of increasing global food demands, rising fertilizer costs and mounting environmental concerns. Efficient nitrogen management is crucial not only for enhancing yield and quality of potato tubers but also for minimizing nitrogen losses that contribute to soil degradation, water pollution and greenhouse gas emissions. As research continues to uncover the physiological and genetic mechanisms behind nitrogen uptake and utilization in potatoes, the integration of this knowledge into breeding programs will be essential. The development of cultivars with high nitrogen use efficiency (NUE) that can perform well under low nitrogen conditions while sustaining high yields will be essential for future sustainable agricultural practices. In addition, there is a growing need to implement site-specific nutrient management (SSNM), supported by real-time monitoring and remote sensing technologies, to provide data-driven recommendations for nitrogen application. Such tools can help optimize the timing, form and amount of nitrogen applied, thereby reducing waste and enhancing efficiency.

Future research should also explore the synergistic effects of combining nitrogen with other nutrients, such as phosphorus and potassium, as nutrient interactions significantly influence plant growth and nutrient dynamics. Furthermore, the role of microbial communities, especially nitrogen-fixing and nitrifying bacteria, should be better understood and harnessed through the development of microbial inoculants or biofertilizers.

Ultimately, improving NUE in potatoes will require a multi-disciplinary approach that includes plant breeders, agronomists, soil scientists, data analysts and farmers. By combining genetic improvements, precision agronomy and environmental stewardship, it will be possible to achieve a sustainable balance between productivity and environmental conservation. This will not only ensure food security but also safeguard the ecological integrity of agricultural landscapes.

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