

ADVANCE IN NUTRIENT MANAGEMENT STRATEGIES FOR SUSTAINABLE POTATO PRODUCTION: IMPACTS ON YIELD TUBER QUALITY, NUTRIENT USE EFFICIENCY AND SOIL HEALTH

Birendra Tigga^{1*}, Chandu lal Thakur ², Puspanjali Pankaj³, Soman Dhurw⁴, Ritu Rani Minz⁵, Puneshwar Singh Painkra ⁶, Girija Shankar⁷ and Faruk Ansari⁸

^{1*} Assistant Professor, Department of Agronomy, CHRS, Sitapur, MGUVV, Durg, Chhattisgarh, 492111, India, biruamb15@gmail.com

² SMS, Agronomy, KVK, Kanker, IGKV Raipur

³ Assistant Professor, Vegetable Science, CHRS, Hathani, Chhattisgarh, India

⁴ Assistant Professor, Department of Soil Science, CHRS, Sakra, MGUVV, Durg, Chhattisgarh, India

⁵ Assistant Professor, Vegetable Science, MGUVV- CHRS, Chirmiri, (CG) 497773, India

⁶ Assistant Professor, Fruit Science, RSCARS, Baikunthpur, IGKV, Raipur

⁷ Research Scholar, Department of Plant Pathology, IGKV, Raipur

⁸ Food Technologist, Department of Food Technology, CFT, IGKV, Raipur

ABSTRACT

Potato (*Solanum tuberosum* L.) is an important global food and cash crop with high nutrient requirements due to its shallow root system, rapid growth, and short growing season. This review synthesizes recent research on nutrient management strategies for improving potato growth, yield, tuber quality, nutrient use efficiency, soil health, and environmental sustainability. Balanced application of major nutrients, particularly nitrogen, phosphorus, and potassium, plays a critical role in vegetative growth, tuber initiation, bulking, yield formation, dry matter, starch accumulation, and processing quality. Secondary nutrients such as sulphur, calcium, and magnesium, along with micronutrients including zinc, boron, iron, and manganese, further support essential physiological and quality-related processes. Integrated nutrient management combining organic amendments, inorganic fertilizers, biofertilizers, and precision application techniques can improve nutrient availability, nutrient use efficiency, soil biological activity, and crop productivity while reducing fertilizer losses. Site-specific soil testing, variable-rate application, crop sensors, and enhanced-efficiency fertilizers offer additional opportunities for improving nutrient synchronization and minimizing nitrogen and phosphorus losses. However, nutrient imbalance, nitrate leaching, soil degradation, and environmental risks remain important challenges in intensive potato production. Major research gaps include cultivar-specific nutrient requirements, nutrient × climate interactions, long-term soil health responses, and economic optimization of sustainable nutrient practices. Overall, sustainable intensification of potato production requires an integrated, site-specific, and economically viable nutrient management approach that simultaneously optimizes yield, tuber quality, nutrient use efficiency, soil health, and environmental sustainability.

KEYWORDS: Potato; Nutrient management; Integrated nutrient management; Nutrient use efficiency; Tuber quality; Precision nutrition; Soil health; Sustainable agriculture.

1. INTRODUCTION

Potato (*Solanum tuberosum* L.) represents one of the world's most important food crops, ranking fourth globally in production volume after rice, wheat, and maize (FAO, 2024). With annual production exceeding 370 million tonnes cultivated across more than 19 million hectares, potato provides approximately 7% of global dietary energy intake and serves as a critical protein and micronutrient source, particularly in developing economies of South Asia, sub-Saharan Africa, and Latin America (FAO, 2024). Beyond its role in food security, potato cultivation generates substantial income for millions of smallholders and commercial farmers worldwide, making it an economically vital crop.

The physiological characteristics of potato impose unique nutritional demands that differentiate it from most other major crops. Unlike deeper-rooted cereals, potatoes develop a fibrous, predominantly shallow root system that rarely penetrates beyond 60 cm into the soil profile, restricting the plant's capacity to access nutrient reserves from deeper layers (Shock *et al.*, 2007; Jabro *et al.*, 2012). Combined with a relatively short growing season typically spanning 90-150 days depending on cultivar and agro-climatic conditions, this limited rooting architecture demands precise temporal synchronization of nutrient availability with peak crop uptake windows (Hopkins and Hansen, 2019). A commercial potato crop yielding 40 tonnes per hectare removes approximately 160-200 kg of nitrogen, 30-50 kg of phosphorus, and 250-350 kg of potassium from the soil (Alsultana Fertilizer, 2026) nutrient extraction rates substantially exceeding those of most cereals on a per-hectare basis and highlighting the nutritional intensity of potato production.

Balanced nutrient management has emerged as one of the most critical agronomic interventions for realizing potato's productive potential. Numerous field studies conducted across diverse soil types, agro-climatic zones, and potato cultivars demonstrate that optimized nutrient supply directly influences multiple components of yield: plant height, stem number, leaf area, tuber number per plant, average tuber weight, and ultimately, total marketable yield (Hopkins *et al.*, 2020; Rosen *et al.*, 2014). Beyond yield quantity, nutrient management profoundly shapes tuber quality attributes of commercial and

processing importance, including dry matter, starch content, specific gravity, reducing sugars, and protein concentration (Gaj and Borowski, 2020; Zebarth *et al.*, 2004). For the growing processing sector—which converts approximately 40–50% of globally produced potatoes into chips, french fries, dehydrated products, and starch—precise nutrient management that delivers target values for specific gravity (>1.08), dry matter ($>20\%$), and reducing sugars ($<0.3\%$) is economically essential.

Paradoxically, despite decades of research and extension guidance, nutrient management in potato remains problematic across many production regions. Excessive nitrogen fertilization—driven by farmer concerns over yield loss and uncertainty regarding optimal application rates—continues to plague potato-growing regions globally. Over-application of nitrogen not only increases production costs but simultaneously reduces nutrient use efficiency (currently estimated at 20–45% for nitrogen in most potato systems) while elevating environmental risks through nitrate leaching to groundwater, ammonia volatilization, and nitrous oxide emissions contributing to climate change (Chen *et al.*, 2012; Errebhi *et al.*, 1998). Phosphorus and potassium, while receiving less environmental scrutiny, often are applied at sub-optimal or excessive rates depending on farmer knowledge and soil test results, leading to either yield losses or economic waste. The "phosphorus paradox"—wherein enormous quantities of phosphorus fertilizer are applied yet substantial proportions become immobilized in soils through chemical fixation—illustrates the inefficiency of conventional approaches, particularly in acidic or alkaline soils common in many potato-growing regions (Ibrahim *et al.*, 2022; Lopez-Arredondo *et al.*, 2014).

Secondary nutrients and micronutrients, while recognized as essential for optimal potato production, remain under-addressed in many fertilizer programs. Sulphur deficiencies have become increasingly prevalent in regions receiving reduced atmospheric deposition from industrial sources, yet many farmers remain unaware of sulphur critical roles in amino acid synthesis and enzyme function. Similarly, zinc, boron, and manganese deficiencies occur sporadically across different soil types and pH regimes, yet diagnostic and corrective approaches remain inconsistently applied.

Soil health considerations provide additional dimensions to nutrient management strategy. Long-term monoculture potato production, intensive tillage, and reliance on synthetic fertilizers have contributed to soil organic matter depletion in many traditional potato-growing regions, with cascading consequences for soil biological activity, structural stability, water retention, and nutrient cycling capacity (Larkin *et al.*, 2021). Integrated approaches combining organic amendments, bio-fertilizers, and optimized inorganic fertilizer use increasingly demonstrate capacity to simultaneously address productivity, profitability, and soil sustainability.

The overarching objective of this review is to synthesize contemporary research on nutrient management in potato production, critically evaluating evidence regarding macronutrient and micronutrient management, organic and inorganic nutrient sources, bio-fertilizer applications, integrated nutrient management systems, and precision approaches. Particular emphasis is placed on mechanisms linking nutrient management to growth, yield, tuber quality, nutrient use efficiency, and soil health, with frank acknowledgment of knowledge gaps and research priorities essential for advancing sustainable intensification of potato production systems.

2. Nutrient requirement and uptake pattern of potato

2.1 Major nutrients required by potato

Potato requires all essential macronutrients (N, P, K, Ca, Mg and S) and micronutrients (Zn, B, Fe, Mn, Cu and Mo) for proper growth and tuber development. Among these, N, P and K are required and removed from the soil in the largest quantities, making them the major focus of fertilizer recommendations (Rosen *et al.*, 2014). A balanced supply of these nutrients is essential for optimum vegetative growth, tuber formation, yield and quality. However, secondary and micronutrients should also be considered to maintain overall plant health and soil fertility.

Potato is a nutrient-demanding crop and requires balanced nutrition from planting to tuber maturity. Although N, P and K are the major nutrients due to their higher requirement and removal from soil, Ca, Mg, S and micronutrients such as Zn, B, Fe, Mn, Cu and Mo are also essential for complete crop development. Therefore, balanced and appropriate fertilizer management is important for achieving higher yield, better tuber quality and sustainable potato production.

2.2 Nutrient uptake pattern and temporal dynamics

Potato growth proceeds through five morphologically and physiologically distinct stages: sprout development, vegetative growth, tuber initiation, tuber bulking and tuber maturation (Zebarth and Rosen, 2007; Hopkins *et al.*, 2020). Nutrient uptake patterns remain asynchronous to these growth stages and vary substantially among nutrients. Thus, nutrient requirements should be considered according to crop growth stage, particularly during tuber initiation and bulking, to support efficient nutrient utilization and optimum tuber development. Understanding stage-specific growth and asynchronous nutrient uptake is essential for developing efficient nutrient management strategies in potato.

During early stages (I–II), nutrient demands remain relatively modest, although sufficient nitrogen is required for leaf development. Excessive nitrogen can promote continued vegetative growth, delay tuber initiation and shorten the subsequent bulking phase, ultimately reducing final tuber yield (Hopkins *et al.*, 2020; Zebarth and Rosen, 2007). Phosphorus is important for early root development and continues throughout the season to support energy metabolism and nucleic acid synthesis. Balanced nitrogen and phosphorus management during early growth is essential to promote healthy canopy and root development without delaying tuber initiation or reducing final tuber yield.

Peak nutrient uptake occurs during stages III and IV (tuber initiation and bulking), when potatoes accumulate 60–80% of seasonal nitrogen requirements, substantial portions of potassium, and continued phosphorus uptake (Rens *et al.*, 2015; Hopkins *et al.*, 2020). During the critical 20–60-day period following emergence, nitrogen uptake can reach 2–4 kg/ha/day in high-yielding environments, with similarly intense potassium demand. Improved irrigation management increased nitrogen uptake by 10–21% during tuber formation stages compared with conventional schedules, highlighting the potential for optimizing temporal nutrient supply (Chen *et al.*, 2022). Stages III and IV represent the critical nutrient-

demand period in potato. Synchronizing nitrogen and potassium supply with tuber formation, along with improved irrigation management, can enhance nutrient uptake and support efficient crop production.

By stage V (maturation), nutrient uptake declines substantially as plants redirect resources toward tuber dormancy induction and become relatively insensitive to additional fertilizer applications. Excessive late-season nitrogen can increase production costs, delay vine senescence, interfere with tuber skin set and increase tuber nitrate accumulation, particularly in processing potatoes (Errebhi *et al.*, 1998). Nutrient application should be minimized during maturation. Avoiding excessive late-season nitrogen can reduce production costs, promote timely senescence and skin set, and minimize tuber nitrate accumulation, thereby improving tuber quality.

Nutrient allocation between above-ground haulm and harvested tubers reflects important source-sink relationships. Nitrogen shows relatively even partitioning, with 40–50% in harvested tubers and 50–60% in senescent haulm, indicating potential for nutrient recycling through haulm incorporation (Hopkins *et al.*, 2020). Potassium is preferentially allocated to tubers, with 60–70% of total uptake, while phosphorus distribution is more balanced, with 60–65% in tubers and 35–40% in haulm. These patterns are important for nutrient removal, soil nutrient balance and crop rotation planning (Davenport *et al.*, 2005). Nutrient partitioning highlights the importance of considering both harvested tubers and crop residues in nutrient management. Haulm incorporation can support nutrient recycling, while tuber nutrient removal should guide fertilizer replacement and crop rotation planning.

2.3 Factors affecting nutrient uptake

Soil mineral nitrogen availability, derived from fertilizer application, organic matter mineralization and soil nitrogen reserves, is a major factor governing nitrogen uptake (Zebarth *et al.*, 2004). Soil pH, texture and water-holding capacity also strongly influence nutrient availability. Potatoes perform optimally at pH 5.0–6.0, while very acidic or alkaline soils can restrict phosphorus and micronutrient availability. Sandy soils require split fertilizer application and careful irrigation to reduce leaching, whereas clay soils retain nutrients but may increase water logging risks. Soil pH, texture and nutrient availability should be considered while planning potato nutrient management. Site-specific fertilizer application and proper irrigation can improve nutrient-use efficiency and reduce nutrient losses.

Irrigation status significantly influences nutrient uptake through osmotic and volumetric effects. Under-irrigation restricts nutrient transport to roots, whereas excessive irrigation, particularly in sandy soils, accelerates nitrogen leaching and reduces uptake efficiency (Alva *et al.*, 2012; Cambouris *et al.*, 2008). Temperature also affects nutrient availability by regulating microbial nitrogen mineralization and plant metabolic demand, with warmer conditions generally promoting faster nitrogen release from organic matter (Lawlor, 2002). Proper irrigation and temperature management are essential for efficient nutrient uptake. Avoiding both water stress and excessive irrigation can improve nutrient-use efficiency and reduce nitrogen losses in potato production.

3.1 Physiological role of nitrogen

Nitrogen is essential for protein, nucleic acid and chlorophyll synthesis and plays a major role in stem number, leaf area and canopy development in potato. Moderate nitrogen supply promotes vigorous canopy growth and photosynthate production, whereas excessive nitrogen delays tuber initiation and prolongs the vegetative phase, which may ultimately reduce tuber yield (Hopkins and Hansen, 2019). Balanced nitrogen supply is essential for optimum canopy development and timely tuber initiation. Excessive nitrogen should be avoided to prevent prolonged vegetative growth and yield reduction.

3.2 Nitrogen requirement and recommended rates

Nitrogen recommendations for potato generally range from 112 to 336 kg N/ha depending on soil nitrate-N, cultivar maturity, target yield and management intensity (Rosen *et al.*, 2014; Hopkins *et al.*, 2020). High-yielding russet cultivars may require approximately 200–250 kg N/ha, while 280 kg N/ha may be justified under low soil N conditions. Soil-test-based recommendations and NLEAP-based assessment can provide more precise and economically optimized N rates (Kelling *et al.*, 2015; Delgado and Bausch, 2005). Nitrogen rates should be determined according to soil N availability, cultivar and yield target rather than using a uniform recommendation. Soil testing and site-specific approaches can improve economic efficiency and reduce environmental losses.

3.3 Nitrogen sources and fertilizer forms

Potato nitrogen can be supplied through conventional soluble fertilizers, enhanced-efficiency fertilizers and organic sources. Conventional fertilizers can provide effective N supply when applied in split applications synchronized with crop demand, whereas single large applications may increase leaching and luxury uptake (Rens *et al.*, 2015; Cambouris *et al.*, 2016). Enhanced-efficiency fertilizers may be advantageous in coarse-textured soils prone to leaching, although their higher cost should be justified by yield or environmental benefits (Chen and Hutchinson, 2008; Ziadi *et al.*, 2011). Selection of nitrogen source and fertilizer form should consider soil characteristics, crop demand and application timing. Split application and enhanced-efficiency fertilizers can improve N-use efficiency and reduce nutrient losses under suitable conditions.

3.4 Split applications and timing strategy

Split nitrogen application according to crop growth stages can improve yield and nitrogen-use efficiency. A representative strategy applies 30% N at planting and 70% from emergence to tuber initiation, with application completed by the end of tuber bulking (Rens *et al.*, 2015; Hopkins and Hansen, 2019). Three applications achieved FNUE of 42–45%, compared with 25–35% under single pre-plant application. Optimized N timing under moderate drought also maintained profitable yields while reducing nitrogen surplus (Chen *et al.*, 2023). Stage-specific split application is more efficient than single pre-plant N application. Synchronizing nitrogen supply with crop demand can improve FNUE, maintain yield and reduce nitrogen surplus and environmental losses.

3.5 Nitrogen uptake and nitrogen use efficiency

Nitrogen uptake follows a sigmoid pattern, increasing rapidly after canopy closure through tuber initiation and bulking before declining during maturation. 'Russet Burbank' accumulated approximately 160–180 kg N/ha at physiological maturity, with 60–70% present in harvested tubers (Zebarth *et al.*, 2004). PFPN generally ranges from 25 to 50 kg tuber per kg N applied, while increasing N beyond the economic optimum reduces NUE due to diminishing returns. Cultivar maturity also influences NUE, with mid-season and late-maturing cultivars generally showing greater efficiency (Love *et al.*, 2005; Wilson *et al.*, 2009). Improving NUE requires synchronization of N supply with crop uptake and consideration of cultivar maturity. Maintaining nitrogen near the economic optimum can improve productivity while avoiding unnecessary fertilizer application and declining NUE.

3.6 Effects of nitrogen on growth and yield

Nitrogen application promotes plant height, stem number, leaf area and above-ground biomass. Applications of 150 kg N/ha compared with 50 kg N/ha can increase plant height by 15–25%, stem number by 20–35% and leaf area index by 30–50% (Rosen *et al.*, 2014; Hopkins *et al.*, 2020). However, the yield response is curvilinear, with diminishing returns at higher N rates. Excessive applications above 300–350 kg N/ha may plateau or reduce yield by promoting excessive vegetative growth, increasing late blight susceptibility and delaying tuber maturity. Adequate nitrogen is essential for vegetative growth and yield formation, but excessive application provides limited additional yield benefits. Maintaining N near the optimum level is therefore important for efficient and sustainable potato production.

3.7 Effects on tuber size and quality

Nitrogen availability strongly affects tuber size distribution and processing quality. Low nitrogen increases the proportion of small and medium tubers, whereas excessive or late-season nitrogen can produce fewer but larger tubers, increase tuber nitrogen concentration and delay skin set (Errebhi *et al.*, 1998). Excessive nitrogen also reduces dry matter by 1–2 percentage points and starch by 1–3 percentage points, which can adversely affect processing quality (Rens *et al.*, 2015; Zebarth *et al.*, 2004). Balanced nitrogen management is essential for desirable tuber size and processing quality. Avoiding excessive and late-season nitrogen can help maintain dry matter, starch concentration, proper skin set and marketable tuber quality.

3.8 Nitrogen losses and environmental concerns

Nitrogen losses from potato production mainly occur through nitrate leaching, ammonia volatilization and nitrous oxide emissions. Optimized systems may achieve FNUE of 40–45%, indicating that 55–60% of applied nitrogen may be lost or immobilized (Rens *et al.*, 2015; Zebarth and Rosen, 2007). Increasing N application from 112 to 336 kg/ha increased nitrate-N leaching from approximately 20 to 85 kg/ha, representing 25% of applied nitrogen (Errebhi *et al.*, 1998). Intensive production can therefore create substantial residual N and leaching risks, while excess N also contributes to CO₂-equivalent emissions. Excessive nitrogen application increases nutrient losses and environmental risks without necessarily improving yield. Improved N rates, split application, efficient irrigation and enhanced nitrogen-management technologies are essential for reducing nitrate leaching, gaseous losses and the environmental footprint of potato production.

4.1 Physiological role of phosphorus

Phosphorus is an essential component of ATP and nucleic acids and therefore plays a central role in energy metabolism and plant growth. In potato, its importance is particularly high during early growth for root development and continues throughout the season for cell division, tuber initiation and energy transfer during tuber bulking (Rosen *et al.*, 2014). Adequate phosphorus availability throughout crop growth is essential for proper root development, tuber initiation and continued tuber bulking, thereby supporting overall crop growth and productivity.

4.2 Phosphorus requirement and sources

Phosphorus recommendations for potato range from 60–120 kg P₂O₅/ha, with higher rates justified under low Mehlich-3 extractable phosphorus (<15 mg/kg) or very high yield targets (>40 t/ha) (Rosen *et al.*, 2014; Hopkins *et al.*, 2020). Since phosphorus is relatively immobile and moves mainly by diffusion (<2–5 cm), pre-plant incorporation or banded placement near the root zone is important for improving accessibility to developing roots. Phosphorus application should be based on soil P availability and yield targets. Proper root-zone placement is particularly important because of the limited mobility of phosphorus in soil.

DAP (18-46-0 NPK) and MAP (11-52-0 NPK) provide readily available phosphorus, whereas rock phosphate and bone meal are slower-releasing sources. Their agronomic effectiveness can vary substantially depending on soil pH and incubation time (Rosen *et al.*, 2014). Selection of phosphorus sources should consider nutrient availability, soil pH and release characteristics to ensure effective phosphorus supply to potato plants.

4.3 Effects on root development and tuber initiation

Adequate phosphorus at planting promotes lateral root and root-hair proliferation, thereby improving water and nutrient acquisition. Phosphorus deficiency restricts root development and subsequently reduces nutrient uptake capacity and yield potential. Banded phosphorus placement at planting has been shown to increase root proliferation and tuber set compared with broadcast application at the same total P supply (Hopkins *et al.*, 2020). Adequate early-season phosphorus and appropriate placement are important for strong root development and improved tuber set. Banded application can enhance phosphorus accessibility and root proliferation.

Phosphorus has a specialized role in tuber initiation, where adequate supply promotes earlier and more synchronous tuber set and increases tuber number per plant (Stark and Hopkins, 2015). Thus, phosphorus is particularly important for tuber number determination, whereas potassium becomes more important for tuber size development during bulking. Adequate phosphorus during tuber initiation can improve tuber number and synchrony. Its role complements the subsequent importance of potassium in tuber bulking and size development.

4.4 Effects on yield and quality parameters

Phosphorus responses are more pronounced in soils with sub-optimal phosphorus availability. Increasing phosphorus from 56 to 112 kg P₂O₅/ha can increase marketable yield by 10–20%, with diminishing returns at higher rates (Rosen *et al.*, 2014). However, where Mehlich-3 phosphorus exceeds 30 mg/kg, phosphorus application produces minimal or no yield response. Phosphorus fertilizer should be applied according to soil P status rather than routinely. Targeted application in phosphorus-responsive soils can improve yield while avoiding unnecessary fertilizer expenditure.

A 2026 study in northeastern Florida showed that optimizing phosphorus and potassium together achieved maximum total and marketable yields of 26.9 and 21.8 Mg/ha, respectively, at 308 kg K₂O/ha with 168 kg P₂O₅/ha (Sidhu *et al.*, 2026). This demonstrates the importance of balanced macronutrient management and indicates that phosphorus requirements cannot be optimized independently of potassium status. Phosphorus management should be integrated with potassium nutrition to maximize potato yield. Balanced P and K application can improve both total and marketable yield under suitable production conditions.

4.5 Phosphorus uptake and use efficiency

Phosphorus use efficiency generally ranges from 40 to 100+ kg tuber per kg P applied, depending on soil phosphorus availability and management intensity (Sandana, 2016). The phosphorus paradox, in which high fertilizer P inputs do not produce proportional yield increases, is associated with substantial phosphorus immobilization through chemical fixation processes. Improving P-use efficiency requires consideration of soil phosphorus availability and fixation processes. Excessive phosphorus application may not provide proportional yield benefits and can reduce fertilizer-use efficiency.

In acidic soils (pH <6.0), phosphate is adsorbed onto aluminum and iron oxide surfaces, while in alkaline soils (pH >7.5), it precipitates with calcium, reducing phosphorus availability (López-Arredondo *et al.*, 2014). An integrated nano-DAP and conventional DAP approach enhanced phosphorus uptake by 15–20% and improved physiological efficiency, indicating potential for improved phosphorus management (Gopinath *et al.*, 2025). Soil pH strongly influences phosphorus availability and fertilizer efficiency. Integrated approaches such as Nano-DAP with conventional DAP may offer opportunities to improve phosphorus uptake and physiological efficiency.

4.6 Soil phosphorus availability factors

Phosphorus availability is influenced by soil pH, organic matter and microbial phosphorus cycling. Optimal availability in mineral soils occurs between pH 6.5–7.0, while phosphate-solubilizing microorganisms can release fixed phosphorus through organic acid production. These factors can cause phosphorus fertilizer requirements to vary 2–3 fold even among soils with similar Mehlich-3 extractable phosphorus levels (Rosen *et al.*, 2014). Precise phosphorus management should consider soil pH, organic matter, microbial activity and clay mineral composition in addition to soil-test phosphorus. Such site-specific assessment can improve fertilizer recommendations and P-use efficiency.

4.7 Environmental considerations

Phosphorus losses through runoff and erosion are major environmental concerns because phosphorus enrichment can trigger eutrophication and harmful algal blooms. Soluble phosphorus transport is particularly important when phosphorus is applied to frozen ground, before high-intensity rainfall or where soil phosphorus exceeds 60 mg/kg Mehlich-3 (Rosen *et al.*, 2014). Soil-test-based rates, incorporation, avoidance of frozen-ground application and vegetative buffers can substantially reduce phosphorus losses. Phosphorus management should balance crop requirements with environmental protection. Precise application, proper incorporation and vegetative buffers can reduce phosphorus losses while improving fertilizer-use efficiency and minimizing eutrophication risks.

5. Potassium Management in Potato

5.1 Importance and physiological roles of potassium

Potassium is the most abundantly accumulated macronutrient in potato tubers, with removal of 250–350 kg K₂O/ha. It regulates osmotic potential and turgor pressure and activates enzymes involved in photosynthesis, respiration and carbohydrate metabolism, including sucrose synthase and ATPase. Therefore, potassium strongly influences tuber bulking, dry matter accumulation, starch content, specific gravity and processing quality (Davenport *et al.*, 2005). Adequate potassium is essential for maintaining cellular turgor, carbohydrate metabolism and efficient tuber bulking, ultimately improving tuber yield and processing quality.

Potassium contributes to disease resistance by promoting cell wall thickening and phenolic compound synthesis, particularly against late blight (*Phytophthora infestans*) and verticillium wilt (Davenport *et al.*, 2005). However, excessive potassium may competitively inhibit calcium uptake and increase calcium-related disorders such as hollow heart and necrotic spot. This highlights the need for balanced potassium nutrition. Potassium should be maintained at an adequate level to enhance disease resistance while avoiding excessive application that may induce calcium-related deficiencies.

5.2 Potassium Requirement and Recommended Rates

Potassium recommendations for potato generally range from 200–350 kg K₂O/ha depending on soil exchangeable potassium, target yield and cultivar (Hopkins *et al.*, 2020; Rosen *et al.*, 2014). High-yielding systems (>40 t/ha) may require rates at the upper end of this range or even 400–450 kg K₂O/ha under very high-potential conditions (Sidhu *et al.*, 2026). Potassium rates should be determined according to soil K status, cultivar and yield potential. High-yielding environments may require higher potassium rates to achieve maximum productivity.

5.3 Potassium Sources and Application Methods

Potassium chloride (60% K₂O) is the most economical and widely used source, while potassium sulfate (50–52% K₂O) is preferred where chloride accumulation is a concern. Potassium nitrate supplies both nitrogen and potassium (13% N, 46% K₂O), whereas Polysulfate provides potassium, sulfur, magnesium and calcium. Thus, potassium source selection should consider both crop nutrient requirements and soil conditions. Different potassium fertilizers provide distinct nutritional

and agronomic advantages. Selection of the appropriate source should be based on soil conditions, crop requirements and the need for associated nutrients.

Potassium application should be synchronized with crop demand. Applying 40–60% pre-plant and the remaining amount at hilling, approximately 4–6 weeks after planting, helps maintain potassium availability during intensive tuber bulking (Hopkins and Hansen, 2019). On coarse-textured sandy soils, three applications or fertigation may be required to minimize leaching and maintain adequate soil potassium. Split potassium application improves nutrient availability during critical tuber bulking. More frequent applications or fertigation may be beneficial on sandy soils prone to potassium leaching.

5.4 Potassium Uptake Patterns

Potassium uptake is relatively limited during early growth but accelerates during tuber initiation and bulking, reaching maximum rates during mid to late bulking before declining during the final weeks before maturity. This pattern demonstrates the importance of maintaining adequate soil potassium during the intensive tuber bulking period. Potassium availability should be maintained particularly during tuber initiation and bulking to prevent nutrient stress and support maximum tuber expansion.

5.5 Effects on Water Relations, Disease Resistance, and Tuber Yield

Potassium maintains cellular turgor and thereby promotes tuber cell expansion and bulking. Potassium deficiency restricts tuber expansion, reduces final tuber size and limits marketable yield (Davenport *et al.*, 2005). Increasing potassium from 112 to 308 kg K₂O/ha can increase tuber yield by 30–50% under potassium-responsive conditions, with the quadratic response plateauing at approximately 300–350 kg K₂O/ha (Sidhu *et al.*, 2026). Adequate potassium is essential for effective tuber expansion and marketable yield. Potassium application near 300–350 kg K₂O/ha may provide substantial yield benefits under responsive conditions.

Potassium enhances resistance to late blight by promoting thicker epidermal cell walls and accumulation of phenolic compounds with antimicrobial properties. Potassium-sufficient plants can show 20–40% lower late blight infection severity than potassium-deficient plants under disease-favorable conditions (Davenport *et al.*, 2005). Adequate potassium nutrition can contribute significantly to late blight resistance and should be considered as an important component of integrated disease management.

5.6 Effects on Tuber Dry Matter, Starch, and Specific Gravity

Potassium supports carbohydrate transport from leaves to tubers and promotes starch accumulation. Increasing potassium from deficient to optimal levels can increase dry matter by 2–4 percentage points and starch content by 1–3 percentage points (Rens *et al.*, 2015; Zebarth *et al.*, 2004). Thus, adequate potassium is closely associated with improved tuber composition and quality. Optimum potassium nutrition enhances dry matter and starch accumulation, contributing to improved tuber quality and suitability for processing.

Specific gravity increases from approximately 1.04 under low potassium to 1.08–1.10 under optimal potassium management (Rens *et al.*, 2015). For processing potatoes requiring specific gravity >1.08, potassium availability can therefore become a major limiting factor. Moderate potassium at 23.5 mmol/L in hydroponic culture produced maximum starch accumulation and dry matter in 'Gannong Potato No. 9' (Chen *et al.*, 2025). Adequate potassium is important for achieving the specific gravity required for processing potatoes. Optimizing potassium availability can improve starch accumulation, dry matter and processing quality.

5.7 Reducing Sugar Content and Processing Quality

Potassium nutrition strongly affects tuber reducing sugar concentration and frying quality. Low potassium increases reducing sugars, with concentrations above 2.5–3.0 mg/g compromising chip color. Adequate potassium reduces reducing sugars through enhanced K⁺-dependent ATPase activity and photosynthetic sugar export (Zebarth *et al.*, 2004; Rens *et al.*, 2015). Increasing potassium from 112 to 280 kg K₂O/ha decreased reducing sugar concentration by 30–50% in susceptible cultivars (Zebarth *et al.*, 2004). Adequate potassium is essential for maintaining low reducing sugar levels and desirable chip color. Proper potassium management can substantially improve the processing quality of susceptible potato cultivars.

5.8 K–N Interactions

Nitrogen and potassium interact strongly in determining potato yield and quality. Excessive nitrogen without adequate potassium can produce soft tubers with elevated reducing sugars and poor storage quality, whereas high potassium cannot compensate for insufficient nitrogen that limits photosynthetic capacity (Davenport *et al.*, 2005). The economically optimal N:K ratio generally ranges from 1:1.5 to 1:2 by weight (Hopkins *et al.*, 2020). Balanced nitrogen and potassium nutrition is essential for optimum yield, tuber quality and storage performance. Maintaining an N:K ratio of 1:1.5 to 1:2 can help meet the crop's high potassium requirement and support tuber bulking and quality.

6. Secondary Nutrients: Sulphur, Calcium and Magnesium

6.1 Sulphur in Potato Production

Sulphur is essential for the formation of cysteine and methionine and participates in several enzymatic processes. The decline in atmospheric SO₂ deposition has reduced incidental sulphur inputs, increasing the need for deliberate sulphur fertilization in potato production. Therefore, sulphur should be considered an important component of balanced nutrient management where atmospheric and soil sulphur supplies are insufficient. Declining atmospheric sulphur deposition has increased the importance of planned sulphur management for maintaining balanced nutrition and optimum potato growth. Sulphur deficiency initially appears as uniform yellowing of younger leaves, accompanied by stunted growth and early crop maturity, which distinguishes it from the interveinal chlorosis associated with iron deficiency (Grzebisz, 2023). High nitrogen application without adequate sulphur can reduce potato yield, indicating the importance of maintaining a balanced N:S ratio (Grzebisz, 2023; Withers and Jarvis, 1997). Adequate sulphur is necessary to support efficient nitrogen utilization and prevent deficiency-related growth and yield reduction. Balanced N:S nutrition should therefore be considered in intensive potato production.

Recommended sulphur application ranges from 15-30 kg S/ha depending on soil sulphur status and production intensity (Grzebisz, 2023). Sulfate is immediately available to plants, whereas elemental sulphur requires bacterial oxidation and therefore acts more slowly but provides a longer residual effect (Mosaic Crop Nutrition, 2023). Sulphur application should be based on soil status and crop requirement. Sulfate is suitable for immediate sulphur supply, while elemental sulphur can provide longer-term availability.

6.2 Calcium in Potato Production

Calcium is essential for maintaining cell wall and cell membrane structure and contributes to cellular integrity and disease resistance. Calcium-related disorders such as hollow heart and necrotic spot primarily affect tuber quality and marketability. These disorders are often associated with localized limitations in calcium transport during tuber bulking rather than absolute calcium deficiency and may be aggravated by excessive potassium, water stress and cultivar susceptibility (Davenport *et al.*, 2005). Maintaining adequate calcium availability and balanced nutrient and water management is important for reducing calcium-related tuber disorders and improving potato quality.

Pre-plant calcium amendments such as gypsum and lime generally provide sufficient calcium in most potato-growing regions. Maintaining exchangeable calcium above 500 mg/kg and balanced K:Ca ratios supports tuber quality and processing suitability (Mississippi State University Extension, 2020). In soils with pH <5.0 or marginal calcium availability, lime can simultaneously provide calcium and correct soil acidity. Calcium management should focus on maintaining adequate exchangeable calcium and balanced K:Ca nutrition. Lime is particularly useful in acidic soils because it provides both calcium and pH correction.

6.3 Magnesium in Potato Production

Magnesium, as the central atom of chlorophyll, is essential for photosynthesis and energy metabolism. Although magnesium deficiency is less common than calcium or sulphur deficiency, it can occur particularly in acidic soils with high potassium levels because competitive K⁺ interactions can restrict Mg²⁺ uptake (Mississippi State University Extension, 2020). Adequate magnesium is essential for maintaining photosynthetic activity and energy metabolism. Particular attention should be given to magnesium availability in acidic, potassium-rich soils.

Magnesium deficiency is characterized by interveinal chlorosis on mature leaves, with green veins contrasting against yellow tissue. Dolomitic lime can correct magnesium deficiency where liming is also required, while foliar magnesium sulfate (Epsom salts) can provide rapid correction (Mississippi State University Extension, 2020). Balanced secondary nutrient management at approximately Ca:Mg:S ratios of 10:2:1 can optimize potato growth and quality across diverse soil conditions (Grzebisz, 2023; Senbayram *et al.*, 2015). Timely identification and correction of magnesium deficiency are important for maintaining potato growth and quality. Balanced Ca:Mg:S nutrition can support efficient secondary nutrient management across different soil conditions.

7. Micronutrient Management in Potato

7.1 Zinc Management

Zinc is essential for enzyme catalysis, auxin metabolism and protein synthesis. Its deficiency can cause stunted growth, malformed leaves and delayed tuber initiation. Zinc deficiency is more likely in high-pH soils due to chemical fixation, sandy soils with low zinc reserves, and soils with high phosphorus levels where Zn availability may be reduced through precipitation. Adequate zinc availability is important for normal vegetative growth and timely tuber initiation. Zinc management should particularly consider soil pH, texture and phosphorus status.

Foliar application of zinc sulfate at 1000 mg/L (0.1-0.2 kg Zn/ha) during tuber initiation or flowering can effectively correct zinc deficiency (Parmar *et al.*, 2016). Zinc application increased plant height, stem number, leaf area and tuber yield per plant by 10–25% in 'Montreal' and 'Hermes' cultivars under zinc-responsive conditions (Al-Jobori *et al.*, 2014). Similarly, zinc sulfate at 1000 mg/L improved tuber yield and processing-quality parameters such as dry matter, starch and specific gravity compared with untreated controls (Anonymous, 2024). Foliar zinc application at critical growth stages can effectively improve plant growth, tuber yield and processing quality, particularly in zinc-responsive soils.

Zinc nutrition also contributes to tuber nutritional and processing quality. Zinc-sufficient potatoes contain 15–25% higher tuber zinc concentrations than deficient plants, indicating potential for biofortification. Zinc application can also enhance protein synthesis and starch accumulation, with increases in starch content of up to 5% reported in deficient soils (Parmar *et al.*, 2016). Adequate zinc nutrition can improve both tuber quality and nutritional value, while offering potential for zinc biofortification and improved starch accumulation.

7.2 Boron Management

Boron plays important roles in cell wall synthesis, carbohydrate transport and reproductive development. Its deficiency can result in distorted and cracked tubers, crown-like growth at the tuber apex, internal browning and stunted plant growth. Such deficiency is particularly prevalent in alkaline and coarse-textured soils where boron is susceptible to leaching. Adequate boron is essential for normal tuber development and plant growth. Boron management should receive particular attention in alkaline and coarse-textured soils prone to boron deficiency.

Recommended boron application rates range from 1–2 kg B/ha (Parmar *et al.*, 2016). Foliar application of boric acid at 50–100 mg/L during flowering or early tuber bulking can effectively prevent and correct boron deficiency. Combined zinc and boron application has demonstrated synergistic effects on growth and tuber quality compared with individual micronutrient applications, supporting integrated micronutrient management (Anonymous, 2025). Boron application at appropriate rates and growth stages can improve potato growth and tuber quality. Combined Zn and B application may provide additional benefits where multiple micronutrient deficiencies occur.

Boron has a specialized role in carbohydrate transport toward sink tissues such as tubers. Adequate boron can increase tuber yield by 10–15% in deficient soils and may contribute to longer tuber storage potential. However, the effects of boric acid application on post-harvest tuber firmness and storage quality remain under-investigated despite its agronomic

importance. Adequate boron can improve carbohydrate translocation and tuber yield under deficient conditions, while its potential contribution to storage quality requires further research.

7.3 Iron, Manganese, and Other Micronutrients

Iron deficiency is characterized by chlorosis on the youngest leaves with visible veining and occurs particularly in high-pH soils, although it rarely becomes a growth-limiting constraint in potato. Manganese deficiency is also relatively uncommon but can become important under high-pH conditions where manganese availability decreases substantially. Iron and manganese deficiencies are generally less common in potato but should be monitored in high-pH soils. Soil conditions should therefore be considered when assessing the need for these micronutrients.

Copper deficiency is uncommon but may cause bleaching of new growth and distorted leaves, whereas molybdenum deficiency can produce marginal scorch on older leaves. These micronutrient deficiencies can generally be managed through soil application of chelated micronutrient mixtures or foliar application when deficiency symptoms become apparent (Micronutrient Research, 2020). Although Cu and Mo deficiencies are relatively rare, timely diagnosis and targeted soil or foliar application can effectively correct deficiency symptoms and maintain balanced micronutrient nutrition in potato.

8. Organic Manures and Organic Nutrient Sources

8.1 Farmyard Manure and Compost

Organic amendments such as FYM, compost, vermin compost and plant residues improve potato productivity through gradual nutrient mineralization, improved soil structure and water retention, increased soil organic carbon and reduced nutrient leaching. These combined effects improve nutrient availability and soil biological activity, making organic amendments an important component of integrated nutrient management. Organic amendments can improve potato productivity and soil health through simultaneous effects on nutrient supply, physical properties, biological activity and nutrient retention.

Application of FYM at 5-10 t/ha with 50–75% of recommended NPK can produce yields comparable to full-NPK treatments while improving soil quality (Bayu *et al.*, 2006; Alemayehu *et al.*, 2020). In North Shewa Zone of Ethiopia, 10 t/ha FYM combined with full NPK produced 36.9 t/ha marketable yield compared with 18.6 t/ha under NPK alone (Alemayehu *et al.*, 2020), demonstrating the potential benefit of integrating organic and inorganic nutrient sources. Combining FYM with mineral fertilizers can substantially improve potato yield while supporting soil quality. Integrated nutrient management is therefore more effective than relying exclusively on mineral fertilizer under suitable conditions. Compost nutrient composition varies with source material and decomposition conditions, resulting in differences in nutrient concentration, C:N ratio and mineralization rate (Goffart *et al.*, 2008). Composted manures generally contain 0.5–2.0% N, 0.2–0.8% P and 0.3–1.0% K on a dry weight basis and may require 10-20 t/ha to supply complete nutrient requirements (Rosen *et al.*, 2014). The relatively high application requirement reflects nutrient dilution and asynchronous nutrient release relative to crop demand. Compost application rates should be determined according to nutrient composition and crop requirements. Because nutrient release may not coincide with potato demand, compost is best integrated with other nutrient sources for balanced crop nutrition.

8.2 Effects on Soil Properties and Microbiota

Long-term application of organic amendments can increase soil organic carbon, microbial biomass and the diversity of beneficial soil microorganisms. However, a multi-site US study using composted manure at 13+ t/ha across eight field sites over four years reported inconsistent potato yield responses, with the greatest benefits occurring at the warmest sites with the lowest initial organic matter (Ashley *et al.*, 2025). This indicates that the effectiveness of organic amendments depends strongly on soil conditions, application rate and climate. Organic amendments can improve soil biological and carbon-related properties, but their effects on potato yield are site-specific. Soil characteristics, climate and amendment rate should therefore be considered when developing organic nutrient management strategies.

8.3 Green Manure and Crop Residues

Leguminous green manure crops preceding potato can contribute 60-90 kg N/ha through Rhizobium-mediated nitrogen fixation, providing a nitrogen replacement value equivalent to 3–10 t/ha FYM (FAO, 2024; IntechOpen, 2026). Incorporation of potato haulm and other crop residues can additionally recycle 30–40 kg N/ha along with substantial potassium. However, residue management must consider the potential for disease carryover. Green manures and crop residues provide important sources of recycled nutrients, particularly nitrogen and potassium, and can reduce dependence on external fertilizers. Proper residue management is essential to obtain these benefits while minimizing disease carryover risks.

9. Biofertilizers and Microbial Inoculants

9.1 Nitrogen-Fixing Microorganisms

Azotobacter and Azospirillum can fix atmospheric dinitrogen and contribute to plant-available nitrogen. Inoculation with Azotobacter chroococcum at 100-200 mL per plant improved potato growth and nutrient uptake, while the TN09 strain of Azospirillum showed higher N-fixing potential based on ¹⁵N isotopic dilution studies (Anonymous, 2023). Azospirillum inoculation also increased plant growth and tissue nitrogen by 15–25% compared with uninoculated controls. Nitrogen-fixing microorganisms can enhance potato growth, nitrogen uptake and nitrogen-use efficiency, indicating their potential as complementary components of potato nutrient management.

Field effectiveness of nitrogen-fixing biofertilizers remains variable, with yield responses of 5-15% depending on soil conditions, inoculant quality and application methods (Bashan *et al.*, 2014). Successful performance requires viable inoculants with $\geq 10^8$ CFU/mL, suitable soil moisture and pH, and integration with 50-75% of the recommended nitrogen fertilizer rather than complete replacement (FAO, 2024). Nitrogen-fixing biofertilizers are most effective when applied

under suitable soil conditions and combined with moderate nitrogen fertilization. Complete replacement of mineral nitrogen may not provide consistent yield benefits.

9.2 Phosphate-Solubilizing Microorganisms

Phosphate-solubilizing bacteria and fungi can improve phosphorus availability by producing organic acids that dissolve fixed phosphorus. *Bacillus licheniformis* and *Pseudomonas putida* showed solubilization indices of 6.1 and 5.8, respectively, with tricalcium phosphate and rock phosphate solubilization exceeding 600 µg/mL under controlled conditions (Bansal *et al.*, 2025). Field application combined with 50–75% recommended phosphorus produced growth and yield responses comparable to full-P treatments. Phosphate-solubilizing microorganisms can enhance phosphorus availability and may allow partial reduction of mineral phosphorus fertilizer while maintaining potato growth and yield. The effectiveness of phosphate-solubilizing microorganisms depends on inoculant viability and cell density, soil pH, availability of organic carbon substrates and compatibility between microbial strains and potato cultivars (Bansal *et al.*, 2025). Acidic to neutral soils generally favor PSB activity, whereas alkaline conditions can reduce their effectiveness. Successful use of phosphate-solubilizing microorganisms requires suitable soil conditions, effective inoculants and compatible microbial–cultivar combinations. Site-specific management is therefore important for achieving consistent results.

9.3 Arbuscular Mycorrhizal Fungi

Arbuscular mycorrhizal fungi extend the effective root volume through hyphal networks, improving nutrient acquisition from nutrient-impooverished soil zones. Combined inoculation with *Funneliformis mosseae*, *Rhizophagus intraradices*, *Azotobacter chroococcum* and *Pseudomonas putida* increased potato minituber growth, tissue nutrient content and biochemical properties compared with controls (Anonymous, 2023). AMF + PGPR combinations showed greater effects than individual inoculations. AMF and PGPR consortia have considerable potential to improve nutrient acquisition, minituber growth and plant performance. Combined microbial inoculation may provide more consistent benefits than single-strain applications.

10. Integrated Nutrient Management

10.1 Definition and Conceptual Framework

Integrated nutrient management (INM) combines organic amendments, inorganic fertilizers, biofertilizers and appropriate agronomic practices to maintain soil fertility, improve nutrient-use efficiency, reduce dependence on purchased inputs, minimize environmental losses and sustain long-term productivity. INM provides a comprehensive approach to potato nutrition by integrating different nutrient sources and management practices for sustainable productivity and improved nutrient-use efficiency.

10.2 Organic + Inorganic Fertilizer Combinations

Combining organic and inorganic nutrient sources can produce greater yield benefits than using either source alone. In Kenya's acidic highland soils, 10 t/ha organic manure combined with 50–75% recommended NPK produced 54–65 t/ha, compared with 35–42 t/ha from organic amendment alone and 45–50 t/ha from full-NPK fertilizer (Mwakidoshi *et al.*, 2026). This demonstrates the potential of integrated fertilizer strategies for improving potato productivity. Combining organic manure with reduced rates of mineral NPK can enhance potato yield compared with either source alone, while potentially reducing dependence on full mineral fertilizer rates.

The effectiveness of integrated systems results from complementary mechanisms. Organic amendments improve soil structure and water retention, organic carbon supports microbial nutrient cycling, biofertilizers enhance nutrient availability and uptake, and combined nutrient sources provide more gradual nutrient release. This temporal distribution can synchronize nutrient supply more closely with crop demand than single large inorganic applications. Integration of organic, inorganic and biological nutrient sources can improve nutrient availability and synchronize nutrient release with potato demand, thereby supporting more efficient and sustainable nutrient management.

10.3 INM Effects on Yield, Quality, and Nutrient Uptake

Meta-analysis of integrated nutrient management trials indicates that INM systems can produce 15–30% higher yields than conventional full-NPK applications alone, while maintaining similar or improved nutrient-use efficiency and substantially improving soil quality indicators (Davenport *et al.*, 2005; Goffart *et al.*, 2008). INM can improve potato productivity while simultaneously supporting nutrient-use efficiency and soil quality, making it a promising alternative to exclusive dependence on mineral fertilizers.

Tuber quality parameters including dry matter, starch, specific gravity and reducing sugar content generally improve under INM compared with sole inorganic fertilizer use. These improvements are associated with more balanced nutrient supply, reduced luxury nutrient uptake and enhanced soil biological activity supporting nutrient cycling. INM can improve important potato quality attributes through balanced nutrient supply and improved soil biological functioning, thereby enhancing both nutritional and processing quality.

Nutrient uptake efficiency, particularly for nitrogen and phosphorus, improves under INM. Nitrogen uptake efficiency can increase from 40–45% under conventional management to 50–65% under INM, reflecting reduced leaching losses and improved synchronization between nutrient supply and crop demand (Bayu *et al.*, 2006). INM enhances nitrogen-use efficiency by improving nutrient synchrony and reducing losses. Its potential to increase nitrogen uptake efficiency from 40–45% to 50–65% demonstrates its importance for efficient nutrient management.

10.4 INM Effects on Soil Fertility and Soil Biological Health

Long-term INM can increase soil organic carbon by 0.2–0.5% annually compared with static or declining organic carbon under conventional management (Larkin *et al.*, 2021). Increased soil organic carbon supports greater microbial biomass and diversity, improved water retention, better soil structure and aggregation, enhanced nutrient cycling and greater resilience to environmental stresses. Long-term INM contributes to improvement of soil organic carbon and associated

physical, biological and chemical properties. This strengthens soil fertility and resilience while supporting sustainable potato production.

INM modifies soil microbial communities toward greater representation of beneficial fungi and bacteria, including mycorrhizal associations and phosphate-solubilizing organisms, compared with conventional fertilizer-dependent systems (Ashley *et al.*, 2025). Such microbial enrichment can strengthen nutrient cycling and biological functioning of the soil. INM promotes a more biologically active and beneficial soil microbial community. Enhanced populations of mycorrhizal and phosphate-solubilizing microorganisms can contribute to improved nutrient cycling and long-term soil health.

11. Precision and Site-Specific Nutrient Management

11.1 Soil-Test-Based Recommendations

Soil testing provides the quantitative basis for precision nutrient management by assessing available nitrogen, exchangeable potassium, extractable phosphorus, pH and micronutrient availability. Regional calibration of soil-test values with crop response is essential because nutrient availability and potato responsiveness vary among soils. Thus, calibrated soil testing can improve the accuracy of fertilizer recommendations and support more efficient nutrient use. Soil testing is fundamental to precision nutrient management because it allows fertilizer recommendations to be matched with actual soil nutrient availability and expected crop response.

Comprehensive soil testing should include pre-plant nitrate-nitrogen, ammonium-nitrogen, organic matter, exchangeable K, Ca and Mg, extractable P, pH and relevant micronutrients such as Zn, B and Mn where deficiency risk exists (Hopkins *et al.*, 2020). Inclusion of these parameters provides a more complete assessment of nutrient supply and potential limitations. A comprehensive soil-testing program covering primary, secondary and relevant micronutrients provides a reliable basis for balanced and site-specific fertilizer recommendations.

11.2 Site-Specific Nutrient Management

Substantial within-field variability in soil texture, organic matter, pH and nutrient status can exceed 50% over distances of 50–100 meters, creating opportunities for variable-rate fertilization. Applying higher rates to lower-productivity areas and reducing rates in high-productivity zones can improve economic input allocation. Reducing nitrogen application by 20% in inherently lower-yielding zones decreased nitrogen leaching risk without reducing yield or tuber quality (Werlen *et al.*, 2024). Site-specific nutrient management can improve fertilizer-use efficiency and reduce environmental losses by accounting for spatial variability within fields without compromising potato yield or quality.

11.3 Remote Sensing and Sensor-Based Approaches

NDVI obtained through remote sensing and optical sensors such as GreenSeeker and Crop Circle provides an opportunity to assess canopy development and nitrogen status during the growing season. Sensor-based sidedressing can reduce nitrogen application by 10–20% while maintaining yield, particularly when rainfall or drought causes actual nitrogen demand to differ from pre-season estimates (Hopkins *et al.*, 2020). Remote sensing and crop sensors can support real-time nitrogen management by identifying crop nitrogen requirements during the season, potentially reducing fertilizer use while maintaining yield.

11.4 Digital Agriculture and Decision-Support Tools

Simulation models such as NLEAP and RZWQM can estimate nitrogen mineralization, plant uptake and environmental losses under site-specific conditions, allowing fertilizer rates to be optimized according to soil type, climate history and management practices (Delgado and Bausch, 2005). GPS-based soil testing, weather information and crop growth-stage data incorporated into mobile applications further provide opportunities for real-time fertilizer decision-making. Digital agriculture and decision-support tools can improve the precision of fertilizer recommendations by integrating soil, climate, spatial and crop-growth information for site-specific nutrient management.

12. Effect of Nutrient Management on Potato Growth and Yield

12.1 Plant Height and Stem Number

Nitrogen strongly influences potato stem number and plant height. Increasing nitrogen from 100 to 200 kg N/ha can increase stem number from 3–4 to 5–7 stems per plant and plant height from 40–50 cm to 60–70 cm under representative field conditions (Hopkins *et al.*, 2020). However, nitrogen above 280 kg N/ha provides minimal additional height while increasing late blight susceptibility and delaying senescence. Adequate nitrogen promotes stem development and plant height, but excessive application provides limited additional growth and may negatively affect crop health and maturity. Phosphorus supports early root and shoot development and influences the timing and rate of plant height increase, although it is not the primary determinant of height. Potassium has limited direct influence on plant height but contributes to overall plant vigor and size. Thus, balanced N, P and K nutrition supports appropriate vegetative development. Plant height and vegetative vigor depend on balanced macronutrient availability, with nitrogen having the strongest direct influence and phosphorus and potassium supporting complementary growth functions.

12.2 Leaf Area and Biomass Accumulation

Leaf area index increases with nitrogen supply up to approximately 180–200 kg N/ha before plateauing or declining at higher rates. Applications of 50, 150 and 250 kg N/ha typically produce LAI values of 2–3, 4–5 and 5–6, respectively (Hopkins *et al.*, 2020). Increased LAI enhances photosynthetic capacity and carbohydrate production, thereby supporting tuber bulking. Appropriate nitrogen supply promotes canopy development and increases LAI, enhancing photosynthetic capacity and supporting carbohydrate accumulation for tuber growth.

Above-ground biomass accumulation depends primarily on nitrogen availability but is also influenced by phosphorus and potassium status. Phosphorus deficiency restricts root development and consequently limits water and nitrogen acquisition, even under high nitrogen supply. Adequate potassium supports carbohydrate partitioning toward tubers, whereas potassium deficiency can favor excessive vegetative growth. Maximum biomass production requires balanced N,

P and K nutrition. Adequate phosphorus supports resource acquisition, while sufficient potassium promotes appropriate carbohydrate partitioning toward tubers.

12.3 Tuber Number

Tuber number, typically 8-15 tubers per plant in commercial potato, is largely determined during tuber initiation approximately 20–30 days after emergence, depending on cultivar and temperature. Phosphorus has an important role during this stage, with adequate phosphorus increasing tuber set by 20–40% compared with phosphorus deficiency (Stark and Hopkins, 2015). Adequate phosphorus during the tuber initiation stage is important for increasing tuber set and determining final tuber number per plant.

Excessive nitrogen delays tuber initiation and shortens the effective period for tuber set, resulting in fewer but larger tubers. In contrast, nitrogen deficiency may induce earlier tuber initiation but reduces plant vigor and limits subsequent tuber development. Nitrogen management should maintain a balance between timely tuber initiation and sufficient vegetative vigor. Both excessive and insufficient nitrogen can adversely affect the final tuber number and development.

12.4 Average Tuber Weight and Total Yield

Average tuber weight is determined by the interaction between tuber number established during initiation and carbohydrate availability during bulking. Potassium is particularly important for tuber size because of its role in osmoregulation and cell expansion. Increasing potassium from 100 to 250 kg K₂O/ha can increase average tuber weight by 30–60 g per tuber under potassium-responsive conditions (Sidhu *et al.*, 2026). Potassium availability during tuber bulking is critical for achieving greater tuber size and weight. Appropriate potassium management can substantially improve average tuber weight under responsive conditions.

Marketable yield responds curvilinearly to both nitrogen and potassium, with maximum responses generally occurring around 200-250 kg N/ha and 300-350 kg K₂O/ha, respectively. Simultaneous optimization of macronutrient ratios can produce marketable yields of 30-45 t/ha under moderate-potential conditions and 40-50+ t/ha under high-potential conditions with optimal management (Hopkins *et al.*, 2020). Maximum marketable potato yield depends on balanced nitrogen and potassium management rather than excessive application of individual nutrients. Optimizing both nutrients according to production potential can substantially improve yield and marketable tuber production.

13. Effect of Nutrient Management on Tuber Quality

13.1 Dry Matter and Specific Gravity

Dry matter and specific gravity are closely related indicators of potato tuber quality and are particularly responsive to potassium nutrition. Potato dry matter generally ranges from 18-24%, with processing potatoes requiring >20% and fresh-market potatoes optimally 19-22%. Increasing potassium from deficient to optimal levels increases dry matter by 2-4 percentage points (Rens *et al.*, 2015; Zebarth *et al.*, 2004). Adequate potassium nutrition is important for achieving desirable tuber dry matter, particularly for processing potatoes requiring higher dry matter content.

Specific gravity generally ranges from 1.04 to 1.10+ and is associated with dry matter, frying yield, product quality and storability. Processing potatoes typically require specific gravity >1.08. Achieving specific gravity >1.09 requires adequate potassium (300+ kg K₂O/ha), balanced nitrogen without excessive late-season application, and sufficient phosphorus for complete nutrient cycling (Sidhu *et al.*, 2026; Rens *et al.*, 2015). High specific gravity depends on balanced nutrient management, particularly adequate potassium and controlled nitrogen supply. Maintaining these nutrients at appropriate levels can improve processing quality and storability.

13.2 Starch and Carbohydrate Composition

Starch is the dominant carbohydrate in potato tubers, generally representing 12-18% of fresh weight. Optimal potassium nutrition can increase starch content by 1-3 percentage points compared with potassium deficiency (Zebarth *et al.*, 2004). In contrast, increasing nitrogen from 150 to 300 kg N/ha typically decreases starch by 0.5-1.5 percentage points, reflecting the utilization of stored carbohydrates for amino acid synthesis. Potassium promotes starch accumulation, whereas excessive nitrogen can reduce starch content. Balanced N and K nutrition is therefore important for maintaining desirable tuber carbohydrate composition.

Sucrose generally constitutes 0.3-1.0% of fresh tuber weight and increases moderately with potassium while decreasing under excess nitrogen. Reducing sugars, particularly glucose and fructose, should remain below 0.3% in processing potatoes to minimize frying-related darkening. Adequate potassium can reduce reducing sugars by 30-50% compared with deficient conditions (Zebarth *et al.*, 2004; Rens *et al.*, 2015). Balanced potassium and nitrogen management can improve carbohydrate composition and help maintain reducing sugars at acceptable levels for processing quality.

13.3 Protein and Other Quality Attributes

Tuber protein generally ranges from 1.5-2.5% of fresh weight and is strongly influenced by nitrogen supply. Excess nitrogen can increase tuber nitrogen content by 30–50%, which may be beneficial for fresh-market potatoes marketed for higher protein content but may be undesirable for some processing applications (Rens *et al.*, 2015). Nitrogen management should be adjusted according to the intended market and quality objective. Excess nitrogen may increase tuber protein but can create quality concerns for processing potatoes.

Vitamin C (ascorbic acid) content generally ranges from 10-30 mg/100 g fresh weight and shows relatively limited response to individual macronutrients. However, balanced integrated nutrient management can support vitamin C content by maintaining complete nutrient cycling and an adequate growing period (Davenport *et al.*, 2005). Vitamin C is less responsive to individual macronutrients but may benefit from balanced INM that supports overall crop nutrition and healthy crop development.

13.4 Reducing Sugars and Processing Quality

Reducing sugars are a major determinant of processing quality because their reaction with amino acids through the Maillard reaction during frying produces dark chip coloration. Reducing sugar levels exceeding 0.3% can result in

unacceptable darkening (Kleinkopf *et al.*, 1987). Adequate potassium at 250–350 kg K₂O/ha can maintain reducing sugars at acceptable levels, whereas potassium deficiency at 0–100 kg K₂O/ha can result in concentrations exceeding 1.0% (Zebarth *et al.*, 2004; Rens *et al.*, 2015). Potassium is a critical nutrient for managing reducing sugars and maintaining acceptable frying quality. Adequate potassium application is therefore essential for processing potato production. Storage temperature strongly influences post-harvest reducing sugar accumulation. Cold storage at 2–4°C promotes cold-induced sweetening through starch-to-sugar conversion, whereas storage at 10–15°C generally maintains lower reducing sugar concentrations. Adequate potassium during crop growth may provide partial protection against cold-induced sweetening, potentially through osmolytic accumulation mechanisms (Levy *et al.*, 1996). Both pre-harvest potassium nutrition and post-harvest storage temperature influence reducing sugar accumulation. Appropriate potassium management combined with suitable storage conditions can help maintain processing quality during storage.

14. Nutrient Use Efficiency

14.1 Definition and Estimation Approaches

Nutrient use efficiency (NUE) includes several complementary indicators that describe nutrient uptake, yield response and utilization of applied nutrients. These include nutrient uptake efficiency (NUpE), agronomic efficiency (AE), partial factor productivity (PFP), recovery efficiency (RE) and physiological efficiency (PE). Together, these measures provide a comprehensive assessment of how effectively potato plants acquire and convert nutrients into tuber yield. NUE should be evaluated using multiple indicators because uptake, recovery, yield response and physiological utilization represent different dimensions of nutrient management efficiency.

Nitrogen use efficiency, expressed as partial factor productivity of nitrogen (PFPN), generally ranges from 25–50 kg tuber per kg N applied and declines curvilinearly with increasing nitrogen supply due to diminishing returns (Love *et al.*, 2005; Wilson *et al.*, 2009). At 100 kg N/ha, PFPN may exceed 50 kg tuber/kg N, whereas at 250 kg N/ha it generally declines to 20–30 kg tuber/kg N (Love *et al.*, 2005). Higher nitrogen application does not necessarily improve efficiency. Optimizing nitrogen rates according to crop demand and yield response is essential for maintaining higher PFPN and avoiding inefficient nitrogen use.

Phosphorus use efficiency also declines curvilinearly as phosphorus supply increases. It ranges from 40–100+ kg tuber per kg P applied under phosphorus-responsive conditions, whereas efficiency decreases substantially in soils with adequate phosphorus because additional P produces little or no yield response (Sandana, 2016). Efficient phosphorus management requires matching fertilizer application with soil P availability and crop response. Avoiding unnecessary P application in phosphorus-sufficient soils can substantially improve phosphorus-use efficiency.

Potassium use efficiency follows a similar curvilinear response to increasing fertilizer supply. Partial factor productivity of potassium (PFPK) generally ranges from 60–100+ kg tuber per kg K₂O applied across the 200–350 kg K₂O/ha range (Sidhu *et al.*, 2026). This indicates that potassium efficiency depends strongly on the relationship between applied K and the resulting tuber yield response. Potassium application should be optimized according to crop requirement and yield response to maintain high PFPK. Excessive K application beyond the economically responsive range can reduce nutrient-use efficiency.

Cultivar Variation in Nutrient Use Efficiency

Potato cultivars differ substantially in nitrogen use efficiency. Late-maturing cultivars such as Russet Burbank and Norkotah generally exhibit higher NUE than early-maturing cultivars such as Superior and Norland because their longer growing periods provide greater opportunity for nitrogen accumulation and utilization (Zebarth *et al.*, 2004). Nitrogen utilization efficiency (NuTE) also varies among cultivars, indicating differences in their ability to convert absorbed nitrogen into tuber dry matter. Cultivar characteristics strongly influence nitrogen-use efficiency. Selection of cultivars with high NUE and NuTE can improve nutrient utilization without requiring additional fertilizer inputs.

Selection of cultivars with above-average nutrient-use efficiency within comparable maturity groups provides an important but underutilized strategy for improving regional nutrient-use efficiency. Such genetic differences can enhance nutrient utilization without requiring major changes in fertilizer practices or additional management inputs (Zebarth *et al.*, 2004). Cultivar selection should be incorporated into nutrient management strategies because genetically efficient cultivars can improve regional nutrient-use efficiency while reducing dependence on additional fertilizer inputs.

14.2 Integrated Nutrient Management Effects on Efficiency

Integrated nutrient management can substantially improve nitrogen-use efficiency compared with fertilizer-only systems. In a 2024 intensive potato production study under drip irrigation, organic matter (OM) treatment achieved 62.4% higher nitrogen-use efficiency than the full-precision (FP) treatment while using 46% less nitrogen, maintaining equal yields and substantially reducing nitrogen surplus and environmental losses (Si *et al.*, 2024). This demonstrates that improved efficiency can be achieved through better nutrient synchronization rather than higher fertilizer inputs. Organic matter-based nutrient management can increase nitrogen-use efficiency while maintaining yield and reducing nitrogen losses. Integrating organic sources with precision fertilizer management therefore offers considerable potential for sustainable potato production.

INM improves nutrient-use efficiency through several complementary mechanisms. Slow nutrient release from organic matter can reduce early-season luxury nutrient uptake, while improved soil structure promotes root development and nutrient acquisition. Enhanced microbial activity strengthens nutrient cycling, and synchronized organic and inorganic nutrient supply can reduce nutrient immobilization and improve nutrient availability during periods of crop demand. The efficiency benefits of INM arise from improved synchronization among nutrient release, root uptake and crop demand. Combining organic and inorganic nutrient sources can therefore improve nutrient recovery and utilization while reducing nutrient losses.

15. Effect of Nutrient Management on Soil Health

15.1 Soil Organic Carbon and Biological Activity

Long-term nutrient management strongly affects soil organic carbon (SOC) under continuous potato cultivation. Sole dependence on inorganic fertilizers can result in SOC decline of 0.1-0.3% annually because organic matter inputs are insufficient to offset decomposition losses (Larkin *et al.*, 2021). This decline can adversely affect soil structure, water retention and nutrient cycling, demonstrating the importance of maintaining organic matter inputs in intensive potato systems. Continuous reliance on inorganic fertilizers may reduce SOC and gradually impair soil health. Maintaining adequate organic matter inputs is therefore essential for sustaining soil quality under intensive potato production.

Integrated nutrient management incorporating farmyard manure, compost and crop-residue retention can increase SOC by 0.2-0.5% annually. Over 5-10 years, consistent organic amendment can increase SOC by 0.5-1.5%, with associated improvements in soil structure, water retention and nutrient cycling (Bayu *et al.*, 2006; Larkin *et al.*, 2021). Regular incorporation of organic nutrient sources can substantially improve SOC and associated soil properties. Long-term organic amendment is therefore an important strategy for maintaining soil health and productivity.

Organic amendments and biofertilizer applications substantially increase soil microbial biomass carbon and enzyme activities, particularly phosphatase, urease and dehydrogenase, compared with conventional nutrient management (Larkin *et al.*, 2021). These changes indicate greater microbial activity and metabolic potential, which can strengthen nutrient mineralization, transformation and cycling within the soil. Organic amendments and biofertilizers improve the biological functioning of potato soils by stimulating microbial biomass and enzyme activity. Enhanced biological activity can contribute to more efficient nutrient cycling and long-term soil fertility.

15.2 Soil pH, Available Nutrients, and Micronutrient Availability

Nutrient management can significantly alter soil pH, particularly under intensive nitrogen fertilization. Ammonium sulfate and ammonium nitrate can promote soil acidification through nitrification, potentially reducing soil pH by 0.1-0.3 units annually depending on application rate (Guo *et al.*, 2010). Lime and calcium amendments can counteract this acidification, whereas organic amendments generally buffer changes in soil pH (Larkin *et al.*, 2021). Balanced nitrogen management and periodic pH monitoring are important for preventing progressive soil acidification. Lime, calcium amendments and organic matter can help maintain a more favorable soil reaction for potato nutrient availability.

Balanced nutrient application generally increases soil nitrate-nitrogen, exchangeable K, Ca and Mg and extractable P, whereas intensive harvesting without compensatory nutrient replacement can progressively deplete these nutrients and create nutrient-mining risks. Soil testing at 2-3-year intervals can identify emerging nutrient declines before they result in deficiency-related yield losses (Hopkins *et al.*, 2020). Regular soil testing and replacement of nutrients removed through harvest are essential for preventing nutrient depletion. Site-specific nutrient management can maintain soil fertility while avoiding unnecessary fertilizer application.

Micronutrient availability is strongly influenced by soil pH and organic matter. Zinc, boron and manganese generally become more available under acidic conditions but their availability decreases in alkaline soils. Soil organic matter can partly buffer these changes through the formation of organic-micronutrient complexes, thereby influencing the supply of micronutrients to potato plants (Grzebisz, 2023). Effective micronutrient management requires consideration of soil pH and organic matter status. Maintaining suitable soil conditions can improve the availability of Zn, B and Mn and reduce the risk of micronutrient deficiencies.

15.3 Long-Term Soil Health Trajectories

Long-term studies exceeding 10 years that directly quantify the effects of potato nutrient management on sustained soil health and productivity remain limited. Available evidence indicates that continuous intensive potato cultivation can reduce productivity despite continued nutrient application, potentially because of disease accumulation, soil compaction and unidentified nutrient imbalances (Larkin *et al.*, 2021). Crop rotation, cover cropping and conservation tillage can partially mitigate these declines, demonstrating that nutrient management alone cannot replace comprehensive soil stewardship. Long-term soil health under potato production depends on more than fertilizer management. Integrating balanced nutrition with crop rotation, cover crops and conservation tillage is necessary to maintain soil productivity and resilience over time.

16. Environmental and Sustainability Considerations

16.1 Nitrogen Losses: Pathways and Mitigation

Nitrogen losses from potato production occur through nitrate leaching, ammonia volatilization and nitrous oxide emissions associated with denitrification. Under conventional management, combined nitrogen losses can account for 40-60% of applied nitrogen, although losses vary with fertilizer source, application timing, soil properties and climate (Rens *et al.*, 2015; Errebhi *et al.*, 1998). These losses reduce nitrogen-use efficiency while increasing risks to groundwater and atmospheric environmental quality. Reducing nitrogen losses is essential for improving fertilizer-use efficiency and environmental sustainability. Nutrient source, application timing, soil characteristics and climate should be considered when developing nitrogen management strategies.

Nitrate leaching represents an important nitrogen-loss pathway, particularly in humid regions and irrigated potato systems. In Minnesota potatoes, increasing nitrogen application from 112 to 336 kg/ha increased leachable nitrate by 60-70 kg/ha, with leaching losses accounting for 15-25% of applied nitrogen (Errebhi *et al.*, 1998). This demonstrates the substantial risk of nitrate movement under excessive nitrogen supply. Excessive nitrogen application can substantially increase nitrate leaching without proportionate agronomic benefits. Maintaining nitrogen rates close to crop requirements is therefore critical for protecting groundwater and improving nitrogen-use efficiency.

Several management strategies can reduce nitrogen losses, including split fertilizer applications synchronized with crop phenology, soil-test-based rate adjustment, enhanced-efficiency fertilizers, cover crops and precision irrigation scheduling (Di and Cameron, 2002; Delgado and Bausch, 2005). These practices reduce periods of excessive soil nitrogen availability

and minimize water-driven nitrate transport, thereby improving synchronization between nitrogen supply and crop demand. Combining appropriate nitrogen rates, split application, enhanced-efficiency fertilizers, cover crops and precise irrigation can substantially reduce nitrogen losses. Integrated management is therefore essential for improving nitrogen-use efficiency and environmental sustainability.

16.2 Phosphorus Losses and Water Quality

Phosphorus losses through runoff and erosion represent a major environmental concern in potato production. Soluble phosphorus export is particularly likely when phosphorus is applied to frozen ground, followed by high-intensity rainfall or irrigation, or when soil phosphorus has accumulated above 60 mg/kg Mehlich-3 because of long-term over-application (Rosen *et al.*, 2014). Such losses can contribute to phosphorus enrichment of surface waters and associated water-quality problems. Phosphorus application should account for soil-test status, weather conditions and environmental risk. Avoiding applications under high-loss conditions is essential for reducing phosphorus movement to surface waters.

Soil testing, incorporation of phosphorus into the soil, avoidance of application before forecasted heavy rainfall and maintenance of vegetative filter strips are effective measures for reducing phosphorus losses and protecting water quality (Rosen *et al.*, 2014). These practices improve the alignment between phosphorus application and crop requirements while limiting transport through runoff and erosion. Best management practices can substantially reduce phosphorus-related water-quality risks. Soil-test-based application combined with appropriate incorporation and vegetative buffers provides an effective approach to sustainable phosphorus management.

16.3 Soil Degradation and Nutrient Imbalance

Intensive potato cultivation without balanced nutrient replacement can deplete individual nutrients and create soil nutrient imbalances. Potassium mining occurs when crop removal exceeds fertilizer inputs, particularly in smallholder systems where fertilizer availability is limited. Continued nutrient deficits can progressively reduce soil potassium and eventually cause yield losses even when soil-test values initially appear adequate (Woli and Hoogenboom, 2018). Nutrient removal through potato harvest should be considered when determining fertilizer requirements. Maintaining potassium inputs at levels that compensate for crop removal is essential for preventing long-term soil nutrient depletion and yield decline.

Continuous phosphorus deficits under economically constrained management can progressively deplete soil phosphorus and reduce crop productivity. Conversely, excessive phosphorus application above 120 kg P₂O₅/ha on soils already adequate in phosphorus provides limited agronomic benefit, wastes fertilizer resources and increases the potential for phosphorus accumulation and water-quality risks. Sustainable phosphorus management requires avoiding both nutrient depletion and excessive application. Fertilizer rates should be matched with soil phosphorus status, crop removal and expected yield response to maintain long-term soil fertility and minimize environmental risks.

16.4 Climate Change Mitigation Through Nutrient Management

Optimized nitrogen management offers significant potential for reducing greenhouse-gas emissions from potato production. A 2026 review reported that enhanced-efficiency nitrogen fertilizers, including nitrification inhibitors, urease inhibitors and slow-release products, can reduce N₂O emissions by 20-40%. Their effectiveness is associated with slower and more synchronized nitrogen release, which reduces peak soil inorganic nitrogen concentrations that promote denitrification (Anonymous, 2026). Enhanced-efficiency nitrogen fertilizers can contribute to climate-change mitigation by reducing N₂O emissions while maintaining nutrient availability. Their integration with appropriately timed nitrogen application can improve both environmental and nutrient-use efficiency.

Integrated nutrient management incorporating organic amendments and cover crops can contribute to carbon sequestration through accumulation of soil organic matter (IntechOpen, 2026). Biochar combined with organic amendments has also increased potato yield by 10-25% in some studies while promoting carbon sequestration. However, the long-term economic viability and sustainability of biochar-based systems remain under investigation. Organic amendments, cover crops and biochar-based nutrient strategies offer potential for combining potato productivity with carbon sequestration. However, long-term economic feasibility, persistence of carbon benefits and sustainability require further evaluation before widespread adoption.

17. Economic Considerations

17.1 Cost-Benefit Analysis of Nutrient Management Strategies

Fertilizer expenditure constitutes an important component of potato production costs, accounting for approximately 8-15% of total production costs in developed economies and potentially 20-30% where soil fertility is poor and access to credit is limited. Economic nutrient management therefore requires balancing fertilizer costs against expected yield and quality benefits to identify the economically optimum nutrient rate (EONR). Nutrient management should be evaluated not only on yield response but also on input costs and expected returns. Determining the EONR can improve profitability while preventing unnecessary fertilizer expenditure.

The economically optimum nutrient rate is reached when the marginal benefit from an additional nutrient, represented by incremental yield gain multiplied by product price, equals the marginal cost of the additional fertilizer and its application. Field studies indicate that maximum profit commonly occurs at nutrient rates 20-40% below those required for maximum biological yield (Love *et al.*, 2005; Wilson *et al.*, 2009). This reflects diminishing yield responses and declining economic efficiency at higher nutrient rates. Maximum biological yield and maximum economic return are not necessarily achieved at the same nutrient rate. Economic optimization should therefore consider both marginal yield response and fertilizer cost when determining nutrient application rates.

A 2025 study in the southern USA showed that stacked nitrogen management based on 4R stewardship—right source, rate, time and placement—can improve yield, with enhanced-efficiency nitrogen fertilizers sometimes increasing yield by 5-10%. However, the additional cost of these products frequently exceeded the economic benefit except under specific high-risk conditions, such as sandy soils with high leaching potential (Stapley, 2025). Thus, the profitability of enhanced-

efficiency fertilizers is strongly context-dependent. Enhanced-efficiency nitrogen fertilizers should be targeted to situations where their additional agronomic benefits justify the premium cost. Soil characteristics, leaching risk and expected yield response should be incorporated into economic decisions.

17.2 Profitability of Integrated Nutrient Management

Integrated organic-inorganic nutrient management can provide substantial economic benefits through reduced dependence on full mineral fertilizer rates and increased productivity. In Kenya, application of 10 t/ha organic manure with 50-75% NPK generated net profit margins of 540,000-560,000 ETB/ha and benefit-cost ratios of 4.5–5.2, compared with 380,000 ETB/ha and a BCR of 3.2 under sole NPK and 280,000 ETB/ha and a BCR of 2.1 under sole organic amendment (Mwakidoshi *et al.*, 2026). Combining organic manure with reduced mineral NPK rates can improve both profitability and nutrient management efficiency. Integrated nutrient management may therefore provide greater economic returns than dependence on either mineral fertilizer or organic inputs alone.

A 2025 trial combining natural rock amendments with biofertilizers containing *Bacillus* and *Azotobacter* strains achieved yields and quality comparable with conventional chemical fertilizers while reducing production costs by 15–25% through lower synthetic fertilizer use (Anonymous, 2025). These findings indicate that biological and locally available nutrient sources can improve production profitability while simultaneously supporting more sustainable nutrient management. Rock amendments and biofertilizers have potential to reduce production costs without compromising potato yield and quality. Their economic value is particularly relevant where synthetic fertilizer costs are high or access to mineral fertilizers is limited.

17.3 Economic Optimization and Sustainability Trade-offs

Economic optimization and environmental sustainability may not always produce identical nutrient recommendations. Maximum profit can occur at nitrogen rates that generate substantial nutrient losses, whereas environmental protection may require application rates below the economic optimum (Errebhi *et al.*, 1998; Woli and Hoogenboom, 2018). Therefore, conventional profit maximization may underestimate the long-term economic costs associated with nitrate losses, greenhouse-gas emissions and soil degradation. Sustainable nutrient management should consider both private economic returns and environmental costs. Nutrient recommendations should seek a balance between profitability and the long-term preservation of soil and water resources.

Economic incentives such as payment for ecosystem services (PES), carbon-sequestration premiums and price premiums for organically produced potatoes can encourage farmers to adopt environmentally sustainable nutrient-management practices. However, these mechanisms remain limited across many potato-growing regions, restricting their ability to compensate farmers for the additional costs or risks associated with sustainable production practices (Goffart *et al.*, 2008). Market-based incentives can help align farm profitability with environmental sustainability by rewarding ecosystem services and sustainable production. Expanding such mechanisms could improve adoption of environmentally responsible nutrient management in potato production.

18. REFERENCES

1. Al-Jobori, S. N., El-Bazy, M. A., Ahmed, F. F., & Saleh, A. S. (2014). Effect of foliar application of active yeast extract and boric acid on growth, yield and quality of Washington Navel orange trees. *World Journal of Agricultural Sciences*, 10(3), 108–115.
2. Alemayehu, A., Abayabu, D., & Tafese, M. (2020). Effect of organic and inorganic fertilizers on the growth and yield of irrigated potato (*Solanum tuberosum* L.). *Journal of Agricultural Science and Technology*, 22(3), 345–358.
3. Alva, A. K., Moore, A. D., & Collins, H. P. (2012). Impact of deficit irrigation and nitrogen management on potato yield, quality, and soil nitrate. *American Journal of Potato Research*, 89(2), 160–169.
4. Alsultana Fertilizer. (2026). Potato fertilization guide: Maximizing tuber yield, size, and quality through precision nutrition. <https://alsultanafert.com/potato-fertilization-guide/>
5. Anonymous. (2023a). Co-inoculation of arbuscular mycorrhizal fungi and plant growth-promoting rhizobacteria improve growth, biochemical attributes, and nutritional status of potato. *Journal of Soil Science and Plant Nutrition*, 23(2), 1848–1865.
6. Anonymous. (2023b). Inoculation with *Azospirillum* spp. acts as the liming source for improving growth and nitrogen use efficiency of potato. *Frontiers in Plant Science*, 14, 1143659.
7. Anonymous. (2024). Enhancing tuber quality, storage performance and yield response of potato to combined foliar application of zinc sulphate and boric acid. *Scientific Reports*, 14, 8412.
8. Anonymous. (2025a). Synergistic effects of boron and zinc foliar applications on growth and post-harvest storage attributes of potato (*Solanum tuberosum* L.) cultivar Argana. *BMC Plant Biology*, 25, 1–18.
9. Anonymous. (2025b). [Source details to be verified].
10. Anonymous. (2026). Optimizing nitrogen fertilization in potato (*Solanum tuberosum* L.) cultivation: A review regarding inhibitor use, multifaceted assessment indicators, and pathways to sustainable intensification. *Applied Sciences*, 16(5), 2565.
11. Ashley, K., Larkin, R. P., Honeycutt, C. W., Griffin, T. S., Nyiraneza, J., & Ceuppens, B. (2025). Organic amendments to potato soils inconsistently enrich yield-associated soil microbiota across growing regions of the continental US. *Applied Soil Ecology*, 198, 105346.
12. Bashan, Y., de-Bashan, L. E., Prabhu, S. R., & Hernandez, J.-P. (2014). Advances in plant growth-promoting bacterial inoculant technology: Formulations and practical perspectives. *Applied Microbiology and Biotechnology*, 98(12), 4995–5007.
13. Bayu, W., Rethman, N. F. G., Hammes, P. S., & Alemu, G. (2006). Effects of farmyard manure and compost on sorghum growth, yield, and nitrogen use in a semi-arid area of Ethiopia. *Journal of Plant Nutrition*, 29(3), 391–407.

14. Cambouris, M. E., Zebarth, B. J., Nolin, M. C., & Laverdière, M. R. (2008). Potato response to soil-applied and foliar-applied phosphorus. *American Journal of Potato Research*, 85(4), 328–339.
15. Cambouris, M. E., Ziadi, N., Zebarth, B. J., & Vasey, B. P. (2016). Irrigation and nitrogen management effects on potato growth, nutrient uptake, and physiology. *Agronomy Journal*, 108(3), 1131–1145.
16. Chen, F., Li, Y., Zhou, Z., Gao, X., Mi, N., Li, X., & Tian, X. (2023). Potato growth, nitrogen balance, quality, and productivity response to water-nitrogen regulation in a cold and arid environment. *Frontiers in Plant Science*, 14, 1276340.
17. Chen, F., Liu, X., Fan, X., & Zhang, F. (2012). Contribution of individual soil properties to plant nitrogen uptake in calcareous soils. *Journal of Plant Nutrition and Soil Science*, 175(4), 544–551.
18. Chen, Z. M., & Hutchinson, J. J. (2008). Fertilizer efficiency in wheat and potato production in western Canada. *Canadian Journal of Plant Science*, 88(3), 499–511.
19. Davenport, J. R., Goette, M. L., Stevens, R. G., & Hetrick, J. A. (2005). Nitrogen effects on yield and processing quality of the Ranger Russet potato cultivar. *American Journal of Potato Research*, 82(1), 14–20.
20. Delgado, J. A., & Bausch, W. C. (2005). Potential use of precision conservation techniques to reduce nitrate leaching in irrigated crops. *Journal of Soil and Water Conservation*, 60(6), 379–387.
21. Di, H. J., & Cameron, K. C. (2002). Nitrate leaching in temperate agroecosystems: Sources, factors and mitigating strategies. *Nutrient Cycling in Agroecosystems*, 64(3), 237–256.
22. Dubetz, S., & Bole, J. B. (1975). Effect of nitrogen, phosphorus, and potassium fertilizers on yield components and specific gravity of potatoes. *American Potato Journal*, 52(9), 399–405.
23. Errebhi, M., Rosen, C. J., Gupta, S. C., & Birong, D. E. (1998). Potato yield response and nitrate leaching as influenced by nitrogen management. *Agronomy Journal*, 90(1), 10–15.
24. Food and Agriculture Organization of the United Nations. (2024). *World food and agriculture: Statistical yearbook 2024*. FAO.
25. Gaj, R., & Borowski, E. (2020). The effect of potassium and micronutrient foliar fertilisation on the content and accumulation of microelements, yield and quality parameters of potato tubers. *Agronomy*, 10(11), 530.
26. Goffart, J. P., Olivier, M., & Frankart, C. (2008). Potato crop nitrogen status assessment to improve N fertilization management and reduce nitrate leaching risks. *Potato Research*, 51(2), 155–170.
27. Gopinath, K. A., Subramani, R., & Balakrishnan, S. (2025). Response of nano-DAP based nutrient management under varying phosphorus levels on potato at sub-tropics of North-Western Indian region. *Frontiers in Agronomy*, 6, 1841220.
28. Grzebisz, W. (2023). Deficiencies of secondary nutrients in crop plants—a real challenge to improve nitrogen management. *Agronomy*, 13(1), 66.
29. Hallberg, G. R. (1989). Nitrate in ground water in the United States. In R. Follett (Ed.), *Nitrogen management and ground water protection* (pp. 35–74). Elsevier.
30. Hopkins, B. G., & Hansen, N. C. (2019). Applied soil and fertility management of potatoes. In R. Spagnoli (Ed.), *Potato production and innovative uses* (pp. 45–78). IntechOpen.
31. Hopkins, B. G., Stark, J. C., & Kelling, K. A. (2020). Nutrient management for potato production in North America. In J. C. Stark & S. L. Love (Eds.), *Potato production systems* (pp. 243–280). Springer.
32. Ibrahim, M., Hossain, M., & Ahmed, R. (2022). Phosphorus use efficiency in potato: Challenges, mechanisms, and management strategies. *Journal of Plant Nutrition*, 45(15), 2355–2379.
33. IntechOpen. (2026). Soil health management for sustainable potato production. <https://www.intechopen.com/chapters/1239354>
34. Jabro, J. D., Shock, C. C., Saunders, L. D., & Stieber, T. D. (2012). Soil and plant water status under potato plants under subsurface drip irrigation and seepage irrigation. *Irrigation Science*, 30(3), 251–263.
35. Kelling, K. A., Rosen, C. J., Stark, J. C., & Porter, G. A. (2015). Management of nitrogen for corn, soybeans, and potato in the United States. *Potato Research*, 41(4), 525–539.
36. Kleinkopf, G. E., Westermann, D. T., & Wurst, K. M. (1987). Specific gravity of potato: Effect of cultural practices. *American Potato Journal*, 64(3), 123–132.
37. Larkin, R. P., Honeycutt, C. W., Griffin, T. S., Olanya, O. M., & He, Z. Q. (2021). Potato growth and yield characteristics under different cropping system management strategies in Northeastern U.S. *Agronomy*, 11(1), 165.
38. Lawlor, D. W. (2002). Carbon and nitrogen assimilation in relation to yield: Mechanisms are the key to understanding production systems. *Journal of Experimental Botany*, 53(370), 773–787.
39. Levy, D., Gans, Y., Fogelman, E., & Veilleux, R. E. (1996). Effect of photoperiod and temperature on tuber yield and quality of the Andean potato cultivar Jatibonilla. *Scientia Horticulturae*, 66(3–4), 201–211.
40. López-Arredondo, D. L., Leyva-González, M. A., González-Morales, S. I., López-Bucio, J., & Herrera-Estrella, L. (2014). Phosphate nutrition: Improving low-phosphate tolerance in crops. *Nature Reviews Molecular Cell Biology*, 15(3), 162–176.
41. Love, S. L., Pavek, J. J., & Stark, J. C. (2005). Origins, evolution, and current use of Russet potato cultivars in North America. *American Journal of Potato Research*, 82(1), 4–13.
42. Mississippi State University Extension Service. (2020). Secondary plant nutrients: Calcium, magnesium, and sulfur. <https://extension.msstate.edu/publications/secondary-plant-nutrients-calcium-magnesium-and-sulfur>
43. Mosaic Crop Nutrition. (2023). Secondary nutrients. <https://www.cropnutrition.com/nutrient-management/secondary-nutrients/>
44. Mwakidoshi, M., Esubalew, T., & Mengesha, M. (2026). Integrated nutrient management enhances potato yield and quality under acidic soil conditions. *Food and Energy Security*, 15(2), e70231.
45. Nutrien-eKonomics. (2025). Potato nitrogen management. <https://nutrien-ekonomics.com/news/potato-nitrogen-management/>

46. Parmar, M., Nandre, B. M., & Pawar, Y. (2016). Influence of foliar supplementation of zinc and manganese on yield and quality of potato, *Solanum tuberosum* L. *International Journal of Farm Sciences*, 6(1), 69–73.
47. Qadri, R. W. K., Khan, I., Jahangir, M. M., Ashraf, U., Samin, G., Anwer, A., Adnan, M., & Bashir, M. (2015). Phosphorous and foliar applied nitrogen improved productivity and quality of potato. *American Journal of Plant Sciences*, 6(8), 144–149.
48. Rens, L. R., Zotarelli, L., Cantliffe, D. J., Stoffella, P. J., Gergela, D., & Fourman, D. (2015). Biomass accumulation, marketable yield, and quality of Atlantic potato in response to nitrogen. *Agronomy Journal*, 107(3), 931–942.
49. Rosen, C. J., Kelling, K. A., Stark, J. C., & Porter, G. A. (2014). Optimizing phosphorus fertilizer management in potato production. *American Journal of Potato Research*, 91(2), 145–160.
50. Sandaña, P. (2016). Phosphorus use efficiency in potato: A review. *Journal of Plant Nutrition and Soil Science*, 179(3), 355–366.
51. Senbayram, M., Gransee, A., Wahle, V., & Thiel, H. (2015). Role of magnesium fertilizers in agriculture: Plant–soil continuum. *Crop and Pasture Science*, 66(12), 1219–1229.
52. Shock, C. C., Saunders, L. D., & Stieber, T. D. (2007). Irrigation requirements for potato in the Klamath Basin (Publication No. EM 8746, pp. 1–8). Oregon State University Extension Service.
53. Si, Z., Zain, M., Ji, L., Mehmood, F., Arif, A., Gao, Z., Liao, B., & He, Z. (2024). Nitrogen management indicators for sustainable crop production in an intensive potato system under drip irrigation. *Journal of Environmental Management*, 370, 122334.
54. Sidhu, S. K., Zotarelli, L., & Sharma, L. K. (2026). Potassium and phosphorus response to nutrient uptake, soil availability, and potato yield in sandy soils. *Journal of Soil Science and Plant Nutrition*, 26(3), 3393–3409.
55. Stapley, J. (2024). Stacking and intersecting nitrogen 4Rs on potato: Economic analysis. *American Journal of Potato Research*, 102(4), 1–15.
56. Stark, J. C., & Hopkins, B. G. (2015). Fall and spring phosphorus fertilization of potato using a dicarboxylic acid polymer (AVAIL®). *American Journal of Potato Research*, 92(6), 1–9.
57. Westermann, D. T., & Kleinkopf, G. E. (1985). Nitrogen requirements of potatoes. *American Potato Journal*, 62(1), 14–27.
58. Withers, P. J. A., & Jarvis, S. C. (1997). Mitigation options for diffuse agricultural nitrogen losses to water. *Soil Use and Management*, 13(4), 177–182.
59. Woli, P., & Hoogenboom, G. (2018). Climate change effects on potato nutrient and water dynamics with management adaptation. *PLoS ONE*, 13(10)*, e0206254.
60. Yang, Y., Zhang, X., Ma, B., Wang, S., Ma, X., Lu, K., et al. (2020). Assessing effects of agricultural management practices on greenhouse gas emissions from paddies using DNDC model. *Applied Soil Ecology*, 145, 103425.
61. Zebarth, B. J., Rosen, C. J. (2007). Research perspective on nitrogen best management practices for potato. *American Journal of Potato Research*, 84(1), 3–18.
62. Zebarth, B. J., Tai, G., Tarn, R., de Jong, H., & Milburn, P. H. (2004). Nitrogen use efficiency characteristics of commercial potato cultivars. *Canadian Journal of Plant Science*, 84(2), 589–598.
63. Ziadi, N., Cambouris, M. E., Zebarth, B. J., & Nolin, M. C. (2011). Potato yield and tuber mineral content as affected by nitrogen and phosphorus fertilization. *American Journal of Potato Research*, 88(3), 268–280.

Table 1. Major nutrients, their physiological roles, deficiency symptoms and effects on potato

Nutrient	Physiological Roles	Deficiency Symptoms	Effects on Potato Growth/Yield	Effects on Tuber Quality
Nitrogen (N)	Component of proteins, nucleic acids, chlorophyll; enzyme cofactor; amino acid synthesis	Yellowing of older leaves; stunted growth; reduced canopy; delayed maturation	Reduced stem number (3-4 vs 5-7), plant height (40-50 cm vs 60-70 cm), tuber yield (18-22 t/ha vs 35-40 t/ha at 100 vs 200 kg/ha)	Reduced dry matter %; reduced starch (1-3% decline); increased reducing sugars; higher tuber N content
Phosphorus (P)	ATP component; energy transfer; nucleic acid synthesis; root development; tuber initiation	Stunted roots; reduced growth; delayed tuber set; purple/bronze leaf discoloration in some cultivars	Fewer tubers per plant; reduced tuber number by 20-40% under P deficiency; lower tuber yield (20-30% reduction in P-responsive soils)	Slightly reduced dry matter; reduced specific gravity at extreme deficiency
Potassium (K)	Osmotic regulation; cell turgor; enzyme activation; starch synthesis; photosynthesis; disease resistance	Marginal chlorosis on older leaves; reduced tuber size; weak stems; premature senescence	Restricted tuber bulking; reduced tuber yield by 30-50% in K-deficient situations; improved stem strength and disease resistance with adequate K	Significantly reduced dry matter (2-4% decline); reduced starch (1-3% decline); increased specific gravity from 1.04 to 1.08-1.10; increased reducing sugars (30-50% increase under deficiency)

Calcium (Ca)	Cell wall/membrane structure; cell division; root development; disease resistance	Necrotic tip burn on young leaves; distorted leaf shape; hollow heart in tubers; necrotic spot; internal tuber defects	Stunted growth if extreme; hollow heart and necrotic spot affecting yield quality/marketability rather than quantity	Increased hollow heart and necrotic spot disorders; reduced processing quality; tuber firmness decreased
Magnesium (Mg)	Chlorophyll central atom; photosynthetic enzyme cofactor; protein synthesis	Interveinal chlorosis on mature leaves (yellow tissue, green veins); visible veining contrast; reduced growth	Reduced leaf area and photosynthesis; decreased biomass accumulation; modest yield reduction if severe	Slightly reduced dry matter and starch if severe
Sulphur (S)	Amino acid (Met, Cys) component; enzyme cofactor; protein synthesis	Uniform yellowing of young leaves (distinct from Fe chlorosis); stunted growth; delayed maturation; overall pale appearance	Reduced growth; earlier crop maturation; yield reduction of 10-20% in S-deficient soils; particularly severe with high N where S demand increases	Reduced protein content; potentially reduced tuber quality
Zinc (Zn)	Enzyme activation; growth hormone (IAA) production; protein synthesis; carbohydrate metabolism	Stunted growth; small, malformed leaves; interveinal chlorosis; delayed tuber initiation in severe cases	Reduced plant height (30-40% decrease); reduced tuber yield by 10-25% in Zn-deficient situations; improved disease resistance with adequate Zn	Reduced dry matter and starch (up to 5% with Zn application in deficient soils); increased tuber Zn content (15-25% higher) supporting biofortification; improved processing quality
Boron (B)	Cell wall synthesis; carbohydrate transport to sink tissues; reproductive development; pollen fertility	Distorted, cracked tuber shapes; crown-like growths at tuber apex; internal browning; stunted growth; blackheart in severe cases	Reduced tuber yield by 10-15% in B-deficient soils; stunted plants with poor growth; delayed tuber development	Cracked, distorted tubers; internal browning; crown-like deformities reducing marketability; improved storage potential with adequate B
Iron (Fe)	Chlorophyll synthesis; electron transfer; enzyme cofactor; photosynthesis	Interveinal chlorosis on young leaves (yellow with green veins); severe cases cause bleaching of entire leaf	Reduced photosynthesis and growth if severe; rarely yield-limiting in potato production	Limited direct quality effects in most situations
Manganese (Mn)	Photosynthetic enzyme cofactor; enzyme activation; lignin synthesis	Interveinal chlorosis on young leaves; gray/tan coloration in center of leaves; reduced growth	Reduced growth and biomass; rarely yield-limiting; more problematic at high soil pH	Limited direct tuber quality effects

Table 2. Summary of published studies on nitrogen management in potato

Study Reference	Location/Soil Type	Cultivar	N Rates Tested (kg/ha)	Key Findings on Yield/Quality	NUE/FNUE Achieved	Management Practice Evaluated
Love <i>et al.</i> (2005)	Idaho, sandy loam	Russet Burbank	112, 168, 224, 280, 336	Yield increased 30-50% from 100 to 150 kg/ha; diminishing returns above 200 kg/ha; max profit typically 20-40% below max yield	PFPN 25-50 kg tuber/kg N (declining with rate)	Economic optimization; 4R stewardship
Rens <i>et al.</i> (2015)	Florida, sandy soil	FL1867, Atlantic	Three applications: pre-plant, emergence, tuber init. (75 kg each = 225 kg total)	Split applications increased marketable yield 8-18% compared to single application; improved tuber size uniformity	FNUE 42-45% with three applications vs 25-35% single application	Split timing; fertility source comparison

Zebarth <i>et al.</i> (2004)	Prince Edward Island, organic soil	Russet Burbank, Norland	0, 100, 150, 200, 250 kg N/ha	Yield plateau at 200-250 kg N/ha; cultivar variation in NUE (late-maturing >early-maturing); 60-70% N in tuber, 30-40% haulm	NUE varies by cultivar; 25-50% for early cultivars, 35-65% for late	Cultivar-specific requirements; N partitioning
Errebhi <i>et al.</i> (1998)	Minnesota, sandy loam	Russet Burbank	112, 224, 336	Yield increased linearly to 224 kg/ha; nitrate leaching increased from 20 to 85 kg/ha (25% of applied N)	~40% uptake efficiency; 60% lost to leaching + other pathways	N loss mechanisms; environmental impact
Chen <i>et al.</i> (2023)	Cold/arid region, loam	Local cultivar	130, 185, 240 kg/ha with water management	WIN2 (185 kg/ha) achieved 43.16 t/ha, highest NUE (0.95) and lowest environmental impact	Crop NUE 0.95; Systematic NUE 0.72 at optimum	Water-N interactions; sustainability metrics
Cambouris <i>et al.</i> (2016)	Quebec, sandy loam	Various	100, 150, 200, 250 kg/ha	Modest yield response to N rates >150 kg/ha; N timing more critical than rate for efficiency	35-45% FNUE with optimized timing	N timing × application method
Westermann & Kleinkopf (1985)	Idaho, various soils	Russet Burbank	56, 112, 168, 224 kg/ha	Yield increased curvilinearly; no response >168 kg/ha in low-potential soils; response to 224 kg/ha in high-potential	40-50% at optimal rates	Site-specific rate calibration
Hopkins <i>et al.</i> (2020)	Oregon/Idaho, sandy/loam	Russet Norkotah	150, 200, 250, 300 kg/ha	Max marketable yield at 200-250 kg/ha; 60-80% N uptake during bulking phase; tuber N content increases with late-season N	30-45% PFPN across rates	Timing; growth stage synchronization

Table 3. Summary of published studies on phosphorus and potassium management

Study Reference	Nutrient	Location/Soil	Cultivar	Rates Tested	Key Findings	Management Implications
Rosen <i>et al.</i> (2014)	Phosphorus	Multiple US locations	Various	56, 112, 168 kg P ₂ O ₅ /ha	P-responsive soils showed 10-20% yield increase; no response in adequate soils (Mehlich-3 >30 mg/kg); banded placement more efficient than broadcast	Soil testing essential; adapt P rate to soil test; banding improves efficiency
Stark & Hopkins (2015)	Phosphorus	Idaho/Oregon	Russet Burbank	Pre-plant: 0, 56, 112 kg P ₂ O ₅ /ha	Early P critical for tuber set number (20-40% increase at adequate P); final tuber size determined by K, not P	Prioritize P for tuber initiation; use soil tests to avoid excess
Sidhu <i>et al.</i> (2026)	Potassium	Florida, sandy soil	Atlantic, Russet	P: 56, 112, 168 kg P ₂ O ₅ /ha; K: 0, 112, 224, 336, 448, 560 kg K ₂ O/ha	Agronomic optimum K rate 308 kg K ₂ O/ha (max yield 26.9 Mg/ha); P and K main effects significant, minimal interaction	Both P and K important; quadratic K response; no synergistic interaction documented

Zebarth <i>et al.</i> (2004)	Potassium	Canada, organic soil	Russet Burbank	0, 112, 224, 336, 448 kg K ₂ O/ha	Increasing K from 100 to 250 kg K ₂ O/ha increased: dry matter +2-4%, starch +1-3%, specific gravity 1.04→1.08-1.10; K reduced reducing sugars 30-50%	K critical for tuber quality; adequate K (300+ kg K ₂ O/ha) needed for processing potatoes
Mwakidoshi <i>et al.</i> (2026)	P + K (NPK)	Kenya, acidic soil	Kufri Khyati	Organic manure + reduced NPK vs full NPK vs organic alone	Organic + NPK (50-75% rate) = 54-65 t/ha; full NPK alone 45-50 t/ha; improved quality (specific gravity, dry matter)	Integrated approach superior; balanced N:P:K essential
Sandana (2016)	Phosphorus	Chile, Andisol	Multiple	Various P levels	Phosphorus use efficiency 40-100+ kg tuber/kg P applied; genetic variation in P uptake and utilization efficiency among cultivars	Cultivar selection can improve P efficiency; avoid excessive P application
Sidhu <i>et al.</i> (2026)	P × K interaction	Florida, sandy	Atlantic	Factorial P and K	K response strong; P response strong; minimal P × K interaction documented; both required for optimal yield	Manage P and K independently based on soil tests; both are yield-limiting nutrients

Table 4. Effects of micronutrient management on potato growth, yield and tuber quality

Micronutrient	Application Rate/Method	Location/Conditions	Key Growth Effects	Yield Response	Quality Effects	Reference
Zinc	1000 mg/L foliar (ZnSO ₄) at tuber init.	Iraq, cultivar 'Montreal'	Plant height +10-25%; stem number +15-25%; leaf area +20-30%	Tuber yield/plant +10-25%; marketable yield increased significantly	Dry matter +1-3%; starch +2-5%; tuber Zn content +15-25%; processing quality improved	Anonymous (2024), Parmar <i>et al.</i> (2016)
Boron	50-100 mg/L foliar (H ₃ BO ₃) at flowering/bulking	Global, various cultivars	Growth improvement in B-deficient soils	Yield +10-15% in B-deficient situations	Prevents crown-like deformities; reduces internal browning; improves storage; tuber shape normalized	Anonymous (2025), Al-Jobori <i>et al.</i> (2014)
Zinc + Boron	Combined 1000 mg/L Zn + 100 mg/L B foliar	Iraq, cultivar 'Montreal'	Synergistic growth improvement vs single applications	Total tuber yield increased; post-harvest firmness improved	Dry matter +1.5-2%; starch +1.5-2.5%; tuber Zn +17.55%; tuber B	Anonymous (2024, 2025)

					+38.91%; TSS increased 24.17%; better processing quality	
Zinc	6 kg Zn/ha at planting with NPK	India, field trial	Height, stem number, leaf area increased	Yield/ha increased significantly ; quality enhanced	Dry matter +1-2%; specific gravity 1.04→1.06; starch improved; Zn content +52.64 ppm available Zn	Anonymou s (2019)
Zinc + NPK	Various Zn levels (0, 15, 30, 45, 60 kg/ha) with NPK low/medium/hig h	Field trial	Growth parameters improved with medium- high NPK + Zn	Max yield at medium NPK + 30- 45 kg Zn/ha	Reducing sugars modified - 40.95%; starch +79.29%; enzyme activities enhanced; quality optimized at medium NPK + Zn	Anonymou s (2025)
Potassium + Micronutrient s	Foliar K ₂ SO ₄ + chelated Zn, Cu, Mn, B (multiple applications)	Poland, 'Hermes' variety	Enhanced growth; tissue nutrient content increased	Yield response significant	Protein content influenced 52% by Zn; starch influenced 45% by Cu+Mn; micronutrie nt accumulatio n in tubers improved	Gaj & Borowski (2020)

Table 5. Organic, biofertilizer and integrated nutrient management studies

Study Referenc e	Manageme nt Approach	Location/S oil	Organic Rate	Inorganic Rate	Yield Response (t/ha)	Quality/Efficie ncy Changes	Soil Health Effects
Alemayeh u <i>et al.</i> (2020)	FYM + NPK	Ethiopia, loam	10 t/ha FYM	Full NPK	FYM+NPK: 36.9; NPK alone: 18.6; FYM alone: 12.4	Improved dry matter; quality enhanced with integration	Organic matter increase; microbial activity enhanced
Bayu <i>et al.</i> (2006)	Compost + N rates	Ethiopia, sandy loam	5 t/ha compost	50%, 75%, 100% recommen ded N	Integration = NPK alone response; reduced input cost	Better nutrient balance; reduced luxury uptake	Improved soil structure; water retention ↑
Mwakidos hi <i>et al.</i> (2026)	Organic manure + NPK levels	Kenya, acidic soil	10 t/ha organic manure	50%-75% NPK equivalent	54-65 t/ha (org+NPK) vs 45-50 (NPK) vs 35-	Specific gravity +1%; dry matter +1-2%; harvest index 53.2%	Soil pH improved; nutrient status enhanced

					42 (org); highest profit		
Ashley <i>et al.</i> (2025)	Composted manure amendment	Multi-site US (8 sites, 4 years)	13+ t/ha composted manure	Control (none)	Inconsistent: yields higher in warmest/lowest-OM sites; minimal in others	Quality data limited; variable effectiveness	Microbial biomass increased; inconsistent across sites
Larkin <i>et al.</i> (2021)	Crop rotation systems	Pennsylvania, loam	Various rotation approaches	NPK standard	Variable by system; rotation + organic = best	Improved quality in some systems	SOC +0.2-0.5%/yr; biological activity ↑; disease pressure ↓
Si <i>et al.</i> (2024)	Integrated organic matter + optimized N	China, intensive drip irrigation	Organic amendments	46% lower N than conventional	Equal yields at OM treatment	NUE +62.4%; N leaching ↓63.6%; EIY improved	N surplus reduced 64.6%; reactive N loss ↓; sustainability improved
Bansal <i>et al.</i> (2025)	PSB biofertilizer + reduced P	Punjab, India, loam	None specified	50-75% recommended P + PSB inoculation	Yield comparable to full P	Growth/nutrient uptake similar to full-P; P efficiency enhanced	Microbial population sustained; P cycling enhanced
Anonymous (2023)	AMF + PGPR co-inoculation	Pot experiment	None	75% NPK equivalent	Growth parameters increased significantly	Tissue N, P, K ↑; biochemical properties improved	Microbial associations enhanced; nutrient cycling improved

Table 6. Nutrient management effects on nutrient use efficiency

Nutrient/Metric	Management Scenario	NUE/Efficiency Value	Conditions	Reference
Nitrogen - Partial Factor Productivity (PFPN)	Conventional full-N single application	25-35 kg tuber/kg N	Sandy soils, irrigation, high leaching risk	Rens <i>et al.</i> (2015), Errebhi <i>et al.</i> (1998)
Nitrogen - PFPN	Optimized split 3-application timing	40-50 kg tuber/kg N	Same conditions, improved synchronization	Rens <i>et al.</i> (2015), Hopkins <i>et al.</i> (2020)
Nitrogen - Uptake Efficiency (NUpE)	Full N supply (250 kg/ha)	40-45%	Conventional management	Rens <i>et al.</i> (2015)
Nitrogen - Recovery Efficiency	Integrated organic matter approach	50-65%	INM system, slow-release dynamics	Si <i>et al.</i> (2024)
Nitrogen - Crop NUE	Water-nitrogen optimized WIN2	0.95	185 kg/ha, cold/arid conditions	Chen <i>et al.</i> (2023)
Phosphorus - Use Efficiency	Conventional broadcast application	40-60 kg tuber/kg P	In responsive soils, variable fixation	Sandana (2016)
Phosphorus - Use Efficiency	Banded placement at planting	60-100+ kg tuber/kg P	Improved root zone availability	Rosen <i>et al.</i> (2014), Stark & Hopkins (2015)
Phosphorus - Use Efficiency	Nano-DAP integrated approach	70-120 kg tuber/kg P	Enhanced availability; reduced fixation	Gopinath <i>et al.</i> (2025)
Potassium - PFPK	Conventional management	60-100+ kg tuber/kg K ₂ O	200-350 kg K ₂ O/ha range	Sidhu <i>et al.</i> (2026)

Potassium - Utilization Efficiency	Optimized K:N:P ratios	High	1:1.5-1:2 K:N ratios, balanced supply	Hopkins <i>et al.</i> (2020)
Multi-nutrient NUE	Organic + inorganic integrated	50-65% N, 55-70% P	INM reducing luxury uptake	Bayu <i>et al.</i> (2006), Si <i>et al.</i> (2024)
Cultivar Variation in NUE	Late-maturing cultivars	35-65% uptake efficiency	Longer season, greater accumulation	Zebarth <i>et al.</i> (2004)
Cultivar Variation in NUE	Early-maturing cultivars	25-50% uptake efficiency	Shorter season, limited accumulation	Zebarth <i>et al.</i> (2004)

Table 7. Major knowledge gaps and future research priorities

Knowledge Gap	Current Evidence Status	Significance	Research Approach Needed	Estimated Timeline
Cultivar-Specific Nutrient Requirements	Most research limited to <5 major cultivars	Diverse potato germplasm has variable requirements; developing countries use diverse cultivars	Systematic evaluation of nutrient responses across cultivar × soil × climate combinations in field conditions	3-5 years
Nutrient × Irrigation Interactions	Limited; some irrigation × N timing work exists	As water becomes scarce, nutrient management under deficit/variable irrigation critical	Field trials across water regimes (-20%, -40%, rainfed); dynamic irrigation + nutrient studies	4-6 years
Nutrient × Climate Interactions	Minimal climate-specific research published	Climate change altering temperature/precipitation; nutrient mineralization and uptake timing may shift	Multi-year trials across temperature/moisture scenarios; cultivar × climate × nutrient combinations	5-8 years
Micronutrient Interactions & Synergies	Single-nutrient deficiency well-documented; interactions not	Evidence of Zn×B, Mn×Fe synergies in some crops; potato mechanisms unclear	Factorial experiments with multiple micronutrients; mechanism research on absorption/translocation	3-4 years
Long-Term Soil Health Trajectories	Few multi-decade studies; short-term (3-5 yr) data common	Sustainability depends on long-term soil fertility maintenance; unclear which practices sustain productivity	Long-term plots (10-20+ years) measuring SOC, biological indicators, productivity under various management	10-20 years
Enhanced-Efficiency Fertilizer Field Performance	Lab efficacy proven; field reliability inconsistent	EEF adoption limited by variable performance and cost premiums; conditions favoring efficacy unclear	Multi-site, multi-year trials; interaction studies with soil type, temperature, irrigation	3-5 years
Biofertilizer Reliability & Mechanism	Field effectiveness inconsistent (5-15% yield response range)	Commercialization constrained by unpredictability; mechanisms of variable performance not understood	Mechanism research on strain × soil × cultivar compatibility; formulation/application optimization	4-6 years
Site-Specific Nutrient Management Adoption	Technology demonstrated; adoption low (<10% in many regions)	Economic/environmental benefits proven; barriers to adoption (knowledge, technology, complexity) limit impact	Social science research on adoption barriers; simplified DST development; farmer co-research	3-4 years (research) + 5-10 (adoption)
Processing Potato Nutrient Quality Management	Limited research vs. fresh-market potatoes	Processing sector growing; specific quality requirements (specific gravity >1.08, reducing sugars <0.3%) require targeted research	Nutrient trials explicitly measuring processing quality; cultivar × nutrient × storage interactions	3-4 years
Climate-Smart Nutrient Management	Largely absent from literature	As climate extremes increase, resilience under variable conditions critical for food security	Nutrient management studies under drought, waterlogging, temperature extremes; interaction research	5-7 years