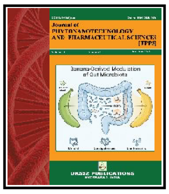
Journal of Phytonanotechnology and Pharmaceutical Sciences 6(1): 11-20, 2026

Online ISSN:2583-0376
http://jpps.ukaazpublications.com
DOI: http://dx.doi.org/10.54085/jpps.2026.6.1.2
Journal of Phytonanotechnology and Pharmaceutical Sciences



Review Article : Open Access

Phytonanotechnology in potato (*Solanum tuberosum* L.): Advances in tuber yield, nutrient use efficiency and stress tolerance

M. Kabilan, K. Sundharaiya*, T. Anitha, M. Jayakumar*** and Adnan A. Khan****◆**
Division of Soil Science and Agricultural Chemistry, Regional Coffee Research Station, Coffee Board of India, Thandigudi-624216, Dindigul, Tamil Nadu, India
** Horticulture Research Station, Kodaikonal-624103, Dindigul, Tamil Nadu, India*
*** Department of Postharvest Technology, Horticultural College and Research Institute, Periyakulam-625604, Theni, Tamil Nadu, India*
**** Regional Coffee Research Station, Coffee Board of India, Thandigudi-624216, Dindigul, Tamil Nadu, India*
***** Division of Nephrology and Hypertension, Department of Medicine, University of California, San Diego, USA*

Article Info

Article history
Received 12 February 2026
Revised 18 March 2026
Accepted 19 March 2026
Published Online 30 March 2026

Keywords
Phytonanotechnology
Solanum tuberosum L.
Nanofertilizers
Nutrient use efficiency
Abiotic stress tolerance
Biofortification
Sustainable agriculture

Abstract

Phytonanotechnology has emerged as an innovative and sustainable approach to address the challenges associated with potato (*Solanum tuberosum* L.) production, particularly in the context of declining soil fertility, inefficient nutrient utilization and increasing biotic and abiotic stresses. This review provides a comprehensive overview of recent advancements in phytomediated nanoparticle synthesis and their applications in potato cultivation. Green synthesis of nanoparticles using plant extracts offers an eco-friendly and cost-effective alternative to conventional methods, producing biocompatible nanomaterials with enhanced functional properties. These phytoengineered nanoparticles play a crucial role in improving tuber yield by enhancing nutrient availability, photosynthetic efficiency and biomass partitioning. The application of nanofertilizers and nanodelivery systems significantly improves nutrient use efficiency (NUE) by enabling controlled and targeted release of macro- and micronutrients, thereby reducing losses due to leaching and volatilization. Furthermore, phytonanotechnology enhances plant tolerance to abiotic stresses such as drought, salinity and temperature extremes by regulating osmolyte accumulation, maintaining ion homeostasis and activating antioxidant defense systems. In addition, nanoparticles exhibit strong antimicrobial properties, contributing to effective management of fungal, bacterial and viral diseases in potato.

Phytonanotechnology also improves tuber quality by enhancing starch content, micronutrient biofortification (Fe and Zn) and the accumulation of phenolics and antioxidants, thereby increasing the nutritional and functional value of potato. Moreover, nano-based post-harvest treatments contribute to improved storage stability and reduced losses. Despite these advantages, challenges such as lack of large-scale field validation, standardization issues, economic feasibility and concerns regarding long-term environmental impacts remain significant barriers to widespread adoption. Future research should focus on the development of smart nano-delivery systems, integration with precision agriculture and the application of omics-based approaches to better understand nanoparticle-plant interactions. The establishment of robust regulatory frameworks and sustainable implementation strategies is essential to ensure safe and effective use. Overall, phytonanotechnology holds great potential to transform potato production systems by enhancing productivity, sustainability and resilience under changing environmental conditions.

1. Introduction

Potato (*Solanum tuberosum* L.) is one of the most important food crops globally, ranking alongside major cereals such as rice, wheat and maize in terms of production and consumption. It plays a critical role in ensuring food and nutritional security, particularly in developing countries where population growth and food demand are rapidly increasing. Potato is highly valued due to its high productivity per unit area, short cropping duration and adaptability to diverse agro-climatic conditions (Devaux *et al*., 2021). In addition to being a major source of carbohydrates, potato provides essential nutrients such as vitamin C, potassium, dietary fiber and several bioactive compounds including phenolics and flavonoids that contribute to human health (Zaheer and Akhtar, 2016; Beals, 2019). Its importance in processed food industries and value-added products further enhances its global economic significance (Devaux *et al*., 2021). Despite its global importance, potato production is constrained by several agronomic, environmental and biological factors. One of the major limitations is poor nutrient use efficiency (NUE), particularly for nitrogen, phosphorus and potassium fertilizers. A significant proportion of applied fertilizers is lost through leaching, volatilization and runoff, resulting in low efficiency and environmental pollution (Kah *et al*., 2018; Dimkpa and Bindraban, 2018). Excessive reliance on chemical fertilizers not only increases production costs but also

Corresponding author: Dr. M. Kabilan
Division of Agricultural Chemistry, Regional Coffee Research Station, Coffee Board of India, Thandigudi-624216, Dindigul, Tamil Nadu, India
E-mail: kabimathi21@gmail.com
Tel.: +91-8825747575

Copyright © 2026 Ukaaz Publications. All rights reserved.
Email: ukaaz@yahoo.com; Website: www.ukaazpublications.com

contributes to soil degradation, disruption of soil microbial communities and greenhouse gas emissions (Raliya *et al*., 2018). In addition to nutrient-related challenges, potato crops are highly susceptible to a wide range of biotic stresses, including fungal, bacterial and viral diseases. Among these, late blight caused by *Phytophthora infestans* remains one of the most devastating diseases, responsible for significant yield losses worldwide (Fry *et al*., 2015).

Abiotic stresses such as drought, salinity and temperature extremes further limit potato productivity, particularly under changing climatic conditions. Drought stress affects water availability and reduces tuber initiation and bulking, while salinity stress disrupts ionic balance and nutrient uptake (Obidiegwu *et al*., 2015). Temperature fluctuations can impair photosynthesis, enzyme activity and metabolic processes, ultimately reducing yield and quality. These stresses often induce oxidative damage through the accumulation of reactive oxygen species (ROS), leading to cellular injury and reduced plant performance (Hasanuzzaman *et al*., 2020). Moreover, post-harvest losses due to improper storage, sprouting and microbial spoilage further reduce marketable yield and economic returns, highlighting the need for innovative solutions in potato production systems. In recent years, nanotechnology has emerged as a transformative approach in agriculture, offering novel solutions to improve crop productivity and sustainability. Nanotechnology involves the manipulation of materials at the nanoscale (1-100 nm), where they exhibit unique physicochemical properties such as increased surface area, enhanced reactivity and improved solubility (Khot *et al*., 2012; Rai and Ingle, 2012). These properties enable the development of nano-fertilizers, nano-pesticides and nanodelivery systems that enhance nutrient availability, reduce losses and improve plant growth and yield (Dimkpa and Bindraban, 2018; Raliya *et al*., 2018). Nanoenabled agricultural inputs have been shown to improve nutrient use efficiency, reduce environmental pollution and enhance stress tolerance in crops (Kah *et al*., 2018). Furthermore, nanotechnology plays a crucial role in precision agriculture by enabling targeted delivery of inputs and real-time monitoring of plant health and soil conditions (Rai *et al*., 2021).

Among various nanotechnological approaches, phytonanotechnology has gained increasing attention due to its eco-friendly and sustainable nature. Phytonanotechnology refers to the synthesis of nanoparticles using plant extracts rich in bioactive compounds such as phenolics, flavonoids, terpenoids and proteins, which act as reducing and stabilizing agents (Iravani, 2011; Singh *et al*., 2018). Unlike conventional physical and chemical synthesis methods, phytomediated synthesis is environmentally benign, cost-effective and does not require toxic chemicals or high energy inputs (Ahmed *et al*., 2016). The resulting phytoengineered nanoparticles are biocompatible and exhibit enhanced functional properties due to the presence of phytochemical capping agents (Singh *et al*., 2018). Recent studies have demonstrated that these nanoparticles can significantly improve plant growth, nutrient uptake and stress tolerance while minimizing environmental risks (Rai *et al*., 2021). The application of phytonanotechnology in potato cultivation offers multiple advantages. Phytoengineered nanoparticles can enhance nutrient use efficiency by facilitating controlled and targeted nutrient delivery, thereby reducing losses and improving nutrient uptake (Dimkpa and Bindraban, 2018). They can also promote plant growth and development by improving photosynthetic efficiency, enzyme activity and hormonal balance. Additionally, these nanoparticles exhibit strong antimicrobial properties, enabling effective management of plant pathogens and reducing the dependence on chemical pesticides (Rai *et al*., 2021). In terms of abiotic stress tolerance, phytonanotechnology enhances antioxidant defense systems, regulates osmolyte accumulation and improves plant resilience under adverse environmental conditions (Hasanuzzaman *et al*., 2020). Furthermore, nano-enabled approaches can contribute to biofortification, improving the nutritional quality of potato tubers by increasing micronutrient content (Dimkpa and Bindraban, 2018).

Another important aspect of phytonanotechnology is its contribution to sustainable agriculture. By reducing the excessive use of chemical inputs, it minimizes environmental pollution and supports soil health. Nanoenabled delivery systems ensure efficient resource utilization, reducing nutrient losses and improving overall system efficiency (Kah *et al*., 2018). Moreover, the biodegradable and non-toxic nature of phytoengineered nanoparticles reduces their adverse effects on non-target organisms, including beneficial soil microbes and pollinators. However, despite these advantages, concerns regarding nanoparticle toxicity, accumulation in soil and plant systems and long-term environmental impacts remain areas of active research (Rai *et al*., 2021). The lack of standardized protocols and limited field-scale studies further highlight the need for comprehensive evaluation and regulatory frameworks. Therefore, this review aims to provide a comprehensive overview of phytonanotechnology in potato, focusing on its role in enhancing tuber yield, improving nutrient use efficiency and mitigating biotic and abiotic stresses. It synthesizes recent advances in the green synthesis of nanoparticles, their interaction with plant systems and their applications in sustainable potato production. Additionally, the review addresses environmental and toxicological concerns and identifies key challenges and future research directions. By integrating current knowledge and emerging trends, this work seeks to contribute to the development of innovative and sustainable strategies for improving potato productivity and resilience under changing environmental conditions.

2. Overview of phytonanotechnology in agriculture

Phytonanotechnology has emerged as a rapidly advancing interdisciplinary field that integrates principles of plant science, nanotechnology and sustainable agriculture to develop eco-friendly solutions for modern crop production challenges. In recent years, increasing concerns regarding environmental degradation, declining soil fertility and inefficient use of agricultural inputs have driven the need for innovative technologies that can enhance productivity while minimizing ecological impact. Within this context, phytonanotechnology offers a promising approach by utilizing plant-derived materials for the synthesis and application of nanoparticles, thereby combining the advantages of nanotechnology with the sustainability of biological systems. The concept revolves around the design, synthesis and application of nanoparticles using plant extracts or plant-based biomolecules, which act as reducing, stabilizing and capping agents. This approach not only reduces the dependency on hazardous chemicals but also enhances the biocompatibility and functional efficiency of nanoparticles in agricultural systems (Iravani, 2011; Singh *et al*., 2018). The scope of phytonanotechnology in agriculture is broad and encompasses multiple domains, including nutrient management, pest and disease control, stress tolerance and crop quality improvement. Nanoparticles synthesized through plant-mediated processes are increasingly being explored as nanofertilizers, nanopesticides and nanocarriers for targeted delivery of agrochemicals.

These applications enable precise and controlled release of nutrients and active compounds, thereby improving their efficiency and reducing losses associated with conventional agricultural practices (Dimkpa and Bindraban, 2018). Furthermore, phytonanotechnology plays a significant role in enhancing plant physiological processes such as photosynthesis, nutrient uptake and enzymatic activities, leading to improved growth and yield. The integration of nanotechnology with plant-based systems also opens new avenues for precision agriculture, where inputs can be applied in a site-specific and time-controlled manner, ensuring optimal resource utilization (Kah *et al*., 2018). As a result, phytonano-technology is increasingly recognized as a key component of next-generation agricultural systems aimed at achieving sustainability and resilience.

Nanoparticles used in agriculture can be broadly classified into several categories based on their composition and functional properties, including metal nanoparticles, metal oxide nanoparticles and polymeric nanoparticles. Metal nanoparticles such as silver (Ag), gold (Au), copper (Cu) and zinc (Zn) are widely studied due to their unique physicochemical properties and strong antimicrobial activity. Among these, silver nanoparticles are particularly well known for their broad-spectrum antimicrobial effects against plant pathogens, making them useful in disease management (Rai *et al*., 2009). Zinc nanoparticles play an essential role in plant nutrition, as zinc is a vital micronutrient involved in enzyme activation and protein synthesis. Similarly, copper nanoparticles exhibit both nutritional and antimicrobial properties, contributing to improved plant health and disease resistance. Gold nanoparticles, although less commonly used in agriculture due to their high cost, have potential applications in biosensing and targeted delivery systems. Metal oxide nanoparticles represent another important class of nanomaterials used in agriculture. These include zinc oxide (ZnO), titanium dioxide (TiO_2), iron oxide (Fe_3O_{22}) and silicon dioxide (SiO,) nanoparticles, which have been extensively studied for their role in enhancing plant growth and stress tolerance. Zinc oxide nanoparticles are widely used as nano-fertilizers due to their ability to improve zinc availability and uptake in plants, thereby enhancing growth and yield (Dimkpa and Bindraban, 2018). Titanium dioxide nanoparticles are known to enhance photosynthetic efficiency by increasing light absorption and promoting electron transport processes. Iron oxide nanoparticles play a crucial role in improving iron nutrition and alleviating iron deficiency in crops, while silicon-based nanoparticles contribute to stress tolerance by strengthening cell walls and enhancing plant defense mechanisms. These nanoparticles exhibit high stability, controlled release properties and compatibility with plant systems, making them suitable for agricultural applications (Khot *et al*., 2012).

Polymeric nanoparticles, including chitosan, alginate and other biodegradable polymers, are gaining increasing attention due to their eco-friendly nature and versatility in agricultural applications. These nanoparticles are primarily used as carriers for the delivery of nutrients, pesticides and growth regulators. Chitosan nanoparticles, derived from chitin, are particularly notable for their biocompatibility, biodegradability and ability to enhance plant growth and immunity. They also exhibit antimicrobial properties and can induce systemic resistance in plants, making them effective in disease management (Raliya *et al*., 2018). Polymeric nanoparticles enable encapsulation and controlled release of active compounds, thereby improving their stability and reducing the frequency of application. This targeted delivery system minimizes environmental contamination and enhances the efficiency of agricultural inputs, aligning with the principles of sustainable agriculture. The synthesis of nanoparticles can be broadly categorized into conventional (physical and chemical) methods and green (biological) approaches. Conventional methods, including chemical reduction, sol-gel processes and physical techniques such as laser ablation and evaporation-condensation, have been widely used for nanoparticle synthesis. However, these methods often involve the use of toxic chemicals, high energy inputs and complex procedures, which limit their sustainability and applicability in agriculture (Iravani, 2011). In contrast, green synthesis approaches utilize biological entities such as plants, microorganisms and enzymes for nanoparticle production. Among these, plant-mediated synthesis has gained significant attention due to its simplicity, cost-effectiveness and scalability. Plant extracts contain a wide range of bioactive compounds that can reduce metal ions into nanoparticles and stabilize them without the need for additional chemicals.

Green synthesis of nanoparticles using plant extracts offers several advantages over conventional methods. It is environmentally friendly, as it eliminates the use of hazardous chemicals and reduces energy consumption. The process is relatively simple and can be carried out under ambient conditions, making it suitable for large-scale production. Additionally, the presence of phytochemicals on the surface of nanoparticles enhances their stability and functional properties, improving their performance in agricultural applications (Singh *et al*., 2018). Phytoengineered nanoparticles are also more biocompatible and less toxic compared to chemically synthesized nanoparticles, making them safer for use in crop production systems. Furthermore, the use of renewable plant resources ensures sustainability and reduces the overall environmental footprint of nanoparticle synthesis. The advantages of phytonanotechnology in sustainable agriculture are multifaceted and extend beyond improved crop productivity. One of the key benefits is the enhancement of nutrient use efficiency through the development of nano-fertilizers that provide controlled and targeted nutrient delivery. This reduces nutrient losses due to leaching and volatilization, thereby minimizing environmental pollution and improving soil health (Dimkpa and Bindraban, 2018). Phytonanotechnology also contributes to effective pest and disease management through the use of nano-pesticides with enhanced efficacy and reduced toxicity. These nano-formulations enable precise targeting of pathogens, reducing the need for excessive pesticide application and lowering the risk of resistance development (Kah *et al*., 2018).

Another important advantage is the role of phytonanotechnology in enhancing plant tolerance to abiotic stresses such as drought, salinity and temperature extremes. Nanoparticles can modulate physiological and biochemical processes, including antioxidant enzyme activity, osmolyte accumulation and hormonal regulation, thereby improving plant resilience under stress conditions (Hasanuzzaman *et al*., 2020). Additionally, phytonanotechnology supports the concept of precision agriculture by enabling site-specific and time-controlled application of inputs, which optimizes resource use and reduces wastage. The integration of nanotechnology with digital tools and sensors further enhances its potential in modern agricultural systems. Environmental sustainability is a central advantage of phytonano-technology. By reducing the reliance on synthetic chemicals and improving input efficiency, it minimizes the negative impacts of agriculture on ecosystems. The biodegradable and non-toxic nature of plant-mediated nanoparticles ensures minimal harm to non-target organisms, including beneficial soil microbes and pollinators. This contributes to the maintenance of soil biodiversity and ecological balance, which are essential for long-term agricultural sustainability (Rai *et al*., 2021). Moreover, phytonanotechnology has potential applications in environmental remediation, including the removal of pollutants from soil and water, further highlighting its versatility. Despite its numerous advantages, the adoption of phytonanotechnology in agriculture faces several challenges. These include the lack of standardized protocols for nanoparticle synthesis and application, limited field-scale validation and concerns regarding long-term environmental and health impacts. Regulatory frameworks for the use of nanoparticles in agriculture are still evolving and there is a need for comprehensive risk assessment to ensure safe and responsible use. Additionally, economic factors such as production cost and accessibility for smallholder farmers must be addressed to facilitate widespread adoption.

3. Green synthesis of nanoparticles using plant extracts

Green synthesis of nanoparticles using plant extracts has gained considerable attention in recent years as a sustainable and environmentally friendly alternative to conventional nanoparticle synthesis methods. This approach utilizes plant-derived biomolecules to reduce metal ions into nanoparticles while simultaneously stabilizing them, thereby eliminating the need for toxic chemicals and energy-intensive processes. The increasing demand for eco-friendly nanomaterials in agriculture has accelerated research into phytomediated synthesis, particularly due to its compatibility with biological systems and reduced environmental risks. Recent studies have highlighted that plant-based nanoparticle synthesis aligns with sustainable agricultural practices by minimizing chemical residues and enhancing biocompatibility (Mgadi *et al*., 2024; Zaman *et al*., 2025). In crop systems such as potato, these nanoparticles are being explored for improving nutrient delivery, stress tolerance and disease resistance.

3.1 Principles and fundamentals of phytomediated nanoparticle synthesis

The synthesis of nanoparticles through plant extracts is based on the principle of bioreduction, where phytochemicals convert metal ions into nanoscale particles. This process occurs under mild conditions and involves the interaction between plant metabolites and precursor metal salts. The nanoscale size (1-100 nm) of these particles imparts unique physicochemical properties such as increased surface area and reactivity, which are crucial for agricultural applications (Handique and Handique, 2025). Unlike conventional methods, phytomediated synthesis integrates reduction and stabilization into a single step, making it efficient and environmentally sustainable. This approach is increasingly recognized as a key strategy in developing next-generation nanoenabled agricultural inputs.

3.2 Role of phytochemicals in reduction, capping and stabilization

Phytochemicals present in plant extracts play a crucial role in nanoparticle synthesis. Compounds such as phenolics, flavonoids, terpenoids and proteins act as natural reducing agents by donating electrons to metal ions, facilitating their conversion into nanoparticles. Additionally, these biomolecules function as capping and stabilizing agents, forming a protective layer around nanoparticles that prevents aggregation and enhances stability. The presence of these bioactive compounds not only stabilizes nanoparticles but also enhances their biological activity, making them more effective in agricultural applications. Recent findings indicate that phytochemical-capped nanoparticles exhibit improved interaction with plant systems and enhanced stress mitigation capabilities (Singh *et al*., 2024).

3.3 Plant sources and extract types for nanoparticle synthesis

A wide variety of plant species and plant parts have been used for nanoparticle synthesis, including leaves, roots, stems, flowers, fruits and agricultural residues. Leaf extracts are most commonly used due to their high concentration of bioactive compounds and ease of preparation. The use of agricultural wastes such as peels and husks further enhances the sustainability of this approach by promoting waste valorization. The choice of plant source significantly influences nanoparticle characteristics such as size, shape and stability. Recent advancements emphasize the use of locally available plant materials to reduce production costs and improve scalability, thereby making phytonanotechnology more accessible for agricultural applications (Hafez *et al*., 2024).

3.4 Mechanisms of nanoparticle formation and growth

The formation of nanoparticles in plant-mediated synthesis involves several stages, including reduction, nucleation, growth and stabilization. Initially, metal ions are reduced into neutral atoms by phytochemicals, followed by nucleation where these atoms aggregate to form small clusters. These clusters grow into nanoparticles through processes such as coalescence and Ostwald ripening. The final stabilization is achieved through capping by plant biomolecules, which prevents aggregation and maintains nanoparticle integrity. The size, morphology and distribution of nanoparticles are largely determined during the nucleation and growth phases. Understanding these mechanisms is essential for tailoring nanoparticles for specific agricultural applications (Kumar *et al*., 2025).

3.5 Factors influencing green synthesis

Several factors influence the efficiency and outcome of green nanoparticle synthesis. pH plays a critical role in determining the ionization state of phytochemicals and affects the reduction rate and stability of nanoparticles. Temperature influence's reaction kinetics, with higher temperatures accelerating nanoparticle formation. The concentration of plant extract and metal precursors determines the rate of nucleation and growth, thereby affecting particle size and yield. Reaction time also plays a significant role, as prolonged reactions may lead to aggregation or changes in particle morphology. Optimization of these parameters is essential for producing nanoparticles with desired properties for agricultural use (Zaman *et al*., 2025).

3.6 Characterization techniques of phytoengineered nanoparticles

Characterization of nanoparticles is essential for determining their physicochemical properties and ensuring their effectiveness in agricultural applications. Techniques such as UV-visible spectroscopy are used to confirm nanoparticle formation, while scanning electron microscopy (SEM) and transmission electron microscopy (TEM) provide information on particle size and morphology. X-ray diffraction (XRD) is used to determine crystalline structure and fourier transform infrared spectroscopy (FTIR) identifies functional groups involved in capping and stabilization. Advanced techniques such as dynamic light scattering (DLS) and zeta potential analysis are used to assess particle size distribution and stability. These characterization methods are crucial for standardizing nanoparticle synthesis and ensuring reproducibility (Singh *et al*., 2024).

3.7 Advantages and limitations of green synthesized nanoparticles

Green synthesized nanoparticles offer several advantages, including eco-friendliness, cost-effectiveness and enhanced biocompatibility. They reduce the use of hazardous chemicals and energy consumption, making them suitable for sustainable agriculture. Additionally, the presence of phytochemicals enhances their functional properties, improving their effectiveness in nutrient delivery, disease control and stress tolerance. However, limitations such as variability in nanoparticle characteristics, lack of standardization and challenges in large-scale production remain significant concerns. Furthermore, the long-term environmental impact and potential accumulation of nanoparticles in soil and plant systems require further investigation (Mgadi *et al*., 2024).

4. Interaction of nanoparticles with potato plants

The interaction of nanoparticles with potato plants involves complex processes that determine their uptake, translocation and physiological effects. Nanoparticles can enter plant systems through root uptake, foliar application and seed priming. Root uptake is the primary pathway, where nanoparticles present in the soil solution are absorbed through root epidermal cells and transported into the vascular system. Foliar application allows nanoparticles to enter through stomata and cuticular openings, while seed priming enhances germination and early seedling development. These pathways enable nanoparticles to interact with plant systems at multiple levels, influencing growth and development (Singh *et al*., 2024). Once inside the plant, nanoparticles are translocated through the xylem and phloem, facilitating their distribution to different plant parts, including leaves, stems and tubers. Xylem transport primarily enables upward movement from roots to shoots, while phloem transport allows bidirectional movement of nutrients and signaling molecules. The efficiency of nanoparticle transport depends on factors such as particle size, surface charge and chemical composition. Smaller nanoparticles with appropriate surface properties are more easily transported within plant tissues (Zaman *et al*., 2025).

At the cellular level, nanoparticles interact with cell walls, membranes and intracellular organelles, influencing various physiological and biochemical processes. They can enhance photosynthetic efficiency, nutrient uptake and enzyme activity, thereby promoting plant growth and productivity. Additionally, nanoparticles can modulate gene expression and phytohormone signaling pathways, contributing to improved stress tolerance and plant resilience (Kumar *et al*., 2025). These interactions highlight the potential of nanotechnology in improving crop performance under diverse environmental conditions. However, the effects of nanoparticles are highly dose-dependent and excessive concentrations may lead to phytotoxicity. High levels of nanoparticles can induce oxidative stress through the generation of reactive oxygen species (ROS), resulting in cellular damage, membrane disruption and inhibition of plant growth. The impact of nanoparticles also varies depending on their size, shape and chemical composition, as well as the plant species and environmental conditions. Therefore, understanding the dose-response relationship and optimizing application rates are essential for ensuring the safe and effective use of nanoparticles in potato cultivation (Mgadi *et al*., 2024).

5. Nanotechnology for enhancing tuber yield

Nanotechnology has emerged as a promising tool for enhancing tuber yield in potato by improving nutrient delivery, physiological efficiency and stress resilience. The unique physicochemical properties of nanoparticles, including high surface area, enhanced reactivity and controlled release behavior, enable efficient interaction with plant systems. In potato cultivation, nano-enabled inputs have been reported to improve growth parameters, increase tuber number and size and enhance overall productivity. Recent studies indicate that nanofertilizers and phytoengineered nanoparticles significantly improve crop performance by optimizing nutrient availability and reducing losses, thereby contributing to higher yield outcomes (El-Ramady *et al*., 2022; Zulfiqar *et al*., 2023).

5.1 Nanofertilizers and controlled nutrient delivery systems

Nanofertilizers represent a major advancement in nutrient management, offering controlled and targeted delivery of essential nutrients. Unlike conventional fertilizers, which release nutrients rapidly and inefficiently, nanofertilizers provide slow and sustained nutrient release, ensuring continuous availability to plants. These nano-formulations can be engineered to release nutrients in response to environmental triggers such as moisture, pH, or root exudates. This targeted delivery enhances nutrient uptake efficiency and minimizes losses through leaching and volatilization (Kumar *et al*., 2022; Shang *et al*., 2021). In potato, nanofertilizers containing nitrogen, zinc and iron have shown significant improvements in plant growth and tuber yield by maintaining optimal nutrient levels throughout the growth cycle.

5.2 Effects on plant growth, root development and tuber initiation

Nanoparticles play a crucial role in promoting plant growth and root development, which are key determinants of tuber initiation in potato. Enhanced root architecture, including increased root length, surface area and branching, improves nutrient and water absorption. This leads to better vegetative growth and early tuber formation. Studies have shown that nanoparticle treatments stimulate cell division and elongation, resulting in improved plant vigor and biomass accumulation (Rastogi *et al*., 2022). In potato, improved root development directly influences stolon formation and tuber initiation, ultimately contributing to increased yield potential.

5.3 Enhancement of photosynthetic efficiency and chlorophyll content

Nanoparticles have been reported to enhance photosynthetic efficiency by improving chlorophyll synthesis, light absorption and electron transport processes. For instance, titanium dioxide (TiO_2) nanoparticles enhance light utilization efficiency, while zinc nanoparticles promote chlorophyll biosynthesis and enzyme activation. These effects lead to increased photosynthetic rates and improved carbon assimilation, which are essential for tuber development (Ahmad *et al*., 2021; Tripathi *et al*., 2023). Enhanced photosynthetic activity ensures a steady supply of assimilates required for tuber bulking and yield enhancement.

5.4 Biomass accumulation and source-sink dynamics

Biomass accumulation and efficient partitioning of assimilates between source (leaves) and sink (tubers) are critical for achieving higher yields in potato. Nanoparticles influence source-sink dynamics by enhancing photosynthetic efficiency and promoting the translocation of carbohydrates to tubers. This results in increased dry matter accumulation and improved tuber size and weight. Studies have demonstrated that nanoenabled treatments enhance the allocation of assimilates towards storage organs, thereby improving yield and quality (Zulfiqar *et al*., 2023). The regulation of hormonal balance by nanoparticles further supports efficient biomass partitioning.

5.5 Role of specific nanoparticles in yield improvement

Different types of nanoparticles play distinct roles in enhancing potato yield. Zinc nanoparticles (ZnNPs) improve enzyme activity, protein synthesis and chlorophyll formation, leading to better plant growth. Iron nanoparticles (FeNPs) enhance iron availability and photosynthetic efficiency, particularly under iron-deficient conditions. Silicon nanoparticles (SiNPs) strengthen plant cell walls, improve stress tolerance and enhance nutrient uptake. Titanium dioxide nanoparticles (TiO, NPs) increase light absorption and photosynthetic activity, thereby boosting plant productivity (El-Ramady *et al*., 2022; Tripathi *et al*., 2023). The combined application of these nanoparticles has shown synergistic effects in improving yield and plant health.

5.6 Seed Nanopriming and early seedling establishment

Seed nanopriming is an emerging technique that involves treating seeds with nanoparticles to enhance germination, seedling vigor and early growth. In potato, nanopriming improves sprouting, root development and uniform seedling establishment. This leads to better crop stand and increased yield potential. Nanoparticles used in seed priming enhance enzymatic activity, water uptake and metabolic processes during germination (Rastogi *et al*., 2022). Improved early growth provides a strong foundation for subsequent plant development and tuber formation.

5.7 Experimental evidence on yield enhancement

Recent experimental studies have demonstrated the effectiveness of nanotechnology in improving potato yield. Field and greenhouse experiments have reported significant increases in plant height, biomass, tuber number and tuber weight following nanoparticle application. For example, zinc oxide nanoparticles have been shown to increase tuber yield by improving nutrient uptake and photosynthetic efficiency, while iron nanoparticles enhance plant growth under nutrient-deficient conditions (El-Ramady *et al*., 2022). Similarly, studies on nanofertilizer applications have reported yield increases of up to 20-30% compared to conventional fertilization methods (Zulfiqar *et al*., 2023). These findings highlight the potential of nanotechnology as a powerful tool for enhancing potato productivity.

6. Improvement of nutrient use efficiency

Nutrient use efficiency (NUE) is a critical factor in sustainable potato production, as it determines the effectiveness with which plants utilize applied nutrients for growth and yield. Improving NUE is essential for reducing input costs, minimizing environmental pollution and enhancing crop productivity. Nanotechnology offers innovative solutions to improve NUE by enabling precise and efficient nutrient delivery systems. The concept of NUE refers to the proportion of applied nutrients that are absorbed and utilized by plants. In potato cultivation, NUE is often low due to inefficient fertilization practices, leading to significant nutrient losses. Conventional fertilizers release nutrients rapidly, resulting in leaching, volatilization and fixation in the soil, which reduces their availability to plants (Shang *et al*., 2021). This not only decreases crop productivity but also contributes to environmental issues such as water pollution and greenhouse gas emissions. Nanoenabled nutrient delivery systems address these limitations by providing controlled and targeted release of nutrients. Nanofertilizers can be designed to release nutrients gradually, ensuring sustained availability throughout the crop growth cycle. This improves nutrient uptake efficiency and reduces losses. Additionally, nanoparticles can enhance the solubility and mobility of nutrients, facilitating their transport to plant roots (Kumar *et al*., 2022). These properties make nano-fertilizers more efficient than conventional fertilizers.

Nanotechnology also improves the uptake of both macro- and micronutrients in potato plants. Enhanced nutrient availability leads to improved physiological processes such as photosynthesis, enzyme activity and metabolic functions. Studies have shown that nanoenabled nutrient delivery increases the uptake of nitrogen, phosphorus, potassium, zinc and iron, resulting in better plant growth and higher yields (El-Ramady *et al*., 2022). Improved nutrient uptake also enhances the nutritional quality of potato tubers. Another significant advantage of nanotechnology is its environmental benefits. By reducing nutrient losses, nanofertilizers minimize soil and water contamination, thereby promoting sustainable agriculture. Controlled nutrient release reduces the risk of over-fertilization and ensures efficient resource utilization. Furthermore, the reduced application frequency of nanofertilizers lowers labor and input costs, making them economically viable for farmers (Zulfiqar *et al*., 2023).

7. Role of phytonanotechnology in abiotic stress tolerance

Abiotic stresses such as drought, salinity and temperature extremes are major constraints limiting potato productivity worldwide, particularly under climate change scenarios. These stresses disrupt physiological, biochemical and molecular processes, leading to reduced growth and yield. Phytonanotechnology has emerged as a promising strategy to enhance plant tolerance against such stresses by modulating stress-responsive pathways, improving nutrient and water use efficiency and activating antioxidant defense systems. Recent studies indicate that phytoengineered nanoparticles can enhance plant resilience by regulating osmolyte accumulation, maintaining cellular homeostasis and improving metabolic efficiency under stress conditions (Nair *et al*., 2023; Verma *et al*., 2024).

7.1 Drought stress mitigation

Drought stress significantly affects potato growth by reducing water availability, impairing photosynthesis and limiting tuber development. Phytoengineered nanoparticles help mitigate drought stress by improving water use efficiency and enhancing root system architecture. Nanoparticles such as silicon (SiNPs) and zinc oxide (ZnO_2 NPs) promote deeper root penetration and increased root surface area, enabling better water absorption. Additionally, nanoparticles regulate stomatal conductance and reduce transpiration losses, thereby maintaining plant water status (Khan *et al*., 2023).

They also enhance the accumulation of osmoprotectants such as proline, soluble sugars and glycine betaine, which help maintain cellular osmotic balance under water-deficit conditions. Furthermore, nano-enabled treatments improve photosynthetic efficiency and chlorophyll stability, contributing to sustained growth during drought stress (Verma *et al*., 2024).

7.2 Salinity stress management

Salinity stress is another major abiotic constraint that affects potato productivity by causing ionic imbalance, osmotic stress and nutrient deficiencies. Excess accumulation of sodium ions (Na_2) disrupts cellular processes and inhibits plant growth. Phytonanotechnology plays a crucial role in mitigating salinity stress by improving ion homeostasis and enhancing nutrient uptake. Nanoparticles such as silicon and iron oxide reduce Naz toxicity by regulating ion transport and maintaining a favorable K_2/Na_2 ratio (Nair *et al*., 2023). Additionally, nanoparticles enhance membrane stability and reduce electrolyte leakage, thereby protecting cellular integrity. They also stimulate antioxidant enzyme activity, reducing oxidative damage caused by salinity-induced stress. These mechanisms collectively improve plant growth and productivity under saline conditions.

7.3 Temperature stress tolerance

Temperature extremes, including heat and cold stress, adversely affect potato growth by disrupting enzymatic activities, membrane stability and photosynthesis. Heat stress reduces tuber formation and increases respiration rates, while cold stress affects cell division and metabolic processes. Phytoengineered nanoparticles enhance temperature stress tolerance by stabilizing cellular structures and protecting photosynthetic machinery. Titanium dioxide (TiO_2) nanoparticles have been reported to improve light utilization and reduce heat-induced damage, while silicon nanoparticles enhance membrane stability under temperature fluctuations (Khan *et al*., 2023). Nanoparticles also regulate the expression of heat shock proteins and stress-responsive genes, enabling plants to adapt to extreme temperature conditions. These effects contribute to improved plant performance and yield under adverse climatic conditions.

7.4 Oxidative stress and antioxidant defense systems

Abiotic stresses often lead to the excessive production of reactive oxygen species (ROS), resulting in oxidative damage to cellular components such as lipids, proteins and nucleic acids. Phytonanotechnology plays a vital role in mitigating oxidative stress by enhancing the plant's antioxidant defense system. Nanoparticles stimulate the activity of key antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT) and peroxidase (POD), which scavenge ROS and protect cells from damage (Verma *et al*., 2024). Additionally, nanoparticles increase the levels of non-enzymatic antioxidants such as ascorbate, glutathione and phenolic compounds. This enhanced antioxidant capacity helps maintain cellular redox balance and ensures normal physiological functioning under stress conditions. The ability of phytoengineered nanoparticles to regulate oxidative stress is a key factor in improving plant resilience and productivity.

8. Role in biotic stress management

Biotic stresses caused by pathogens such as fungi, bacteria and viruses are major threats to potato production, leading to significant yield losses and reduced tuber quality. Conventional disease management strategies rely heavily on chemical pesticides, which pose environmental and health risks. Phytonanotechnology offers an innovative approach to disease management by utilizing nanoparticles with strong antimicrobial properties and targeted delivery systems. Phytoengineered nanoparticles can inhibit pathogen growth, disrupt microbial structures and enhance plant defense mechanisms, thereby providing effective and sustainable disease control (Singh *et al*., 2023; Patel *et al*., 2024).

8.1 Major biotic stresses affecting potato crops

Potato crops are susceptible to a wide range of biotic stresses, including fungal diseases such as late blight (*Phytophthora infestans*) and early blight (*Alternaria solani*), bacterial diseases such as bacterial wilt (*Ralstonia solanacearum*) and viral infections such as potato virus Y(PVY). These diseases significantly reduce yield and quality, often requiring intensive chemical control measures. The increasing resistance of pathogens to conventional pesticides further complicates disease management, highlighting the need for alternative approaches (Patel *et al*., 2024).

8.2 Antimicrobial mechanisms of phytoengineered nanoparticles

Phytoengineered nanoparticles exhibit strong antimicrobial activity through multiple mechanisms. They can disrupt microbial cell membranes, leading to leakage of cellular contents and cell death. Nanoparticles also generate reactive oxygen species that damage microbial DNA, proteins and lipids. Additionally, they can interfere with enzyme activity and metabolic processes in pathogens, inhibiting their growth and reproduction (Singh *et al*., 2023). The small size and high surface area of nanoparticles enable them to penetrate microbial cells effectively, enhancing their antimicrobial efficacy.

8.3 Management of fungal diseases

Fungal diseases are among the most destructive biotic stresses affecting potato crops. Phytoengineered nanoparticles such as silver (AgNPs) and copper oxide (CuO_2NPs) have shown significant antifungal activity against pathogens like *P. infestans* and *A. solani*. These nanoparticles inhibit spore germination, disrupt fungal cell walls and prevent disease spread. Studies have reported that nano-based treatments can significantly reduce disease severity and improve plant health, offering an effective alternative to conventional fungicides (Patel *et al*., 2024).

8.4 Control of bacterial and viral pathogens

Nanoparticles also play a crucial role in controlling bacterial and viral diseases in potato. Metal nanoparticles such as silver and zinc oxide exhibit strong antibacterial activity by disrupting cell membranes and inhibiting enzyme function. In the case of viral pathogens, nanoparticles enhance plant defense mechanisms rather than directly targeting the virus. They induce systemic resistance and strengthen plant immunity, reducing viral replication and spread (Singh *et al*., 2023). This indirect mode of action makes nanoparticles a valuable tool in managing viral diseases.

8.5 Nanopesticides and targeted delivery systems

Nanopesticides represent a significant advancement in plant protection, offering controlled and targeted delivery of active ingredients. These formulations improve pesticide efficiency by ensuring precise application and reducing off-target effects. Nanocarriers can encapsulate pesticides and release them gradually, enhancing their stability and effectiveness. This reduces the frequency of application and minimizes environmental contamination (Verma *et al*., 2024). In potato cultivation, nano-pesticides have shown promising results in improving disease control while reducing chemical inputs.

8.6 Induction of plant defense responses

Phytonanotechnology enhances plant defense mechanisms by inducing systemic acquired resistance (SAR) and induced systemic resistance (ISR). Nanoparticles stimulate the production of defense-related enzymes such as peroxidases, polyphenol oxidases and phenylalanine ammonia-lyase, which strengthen plant immunity. They also promote the accumulation of secondary metabolites such as phenolics and flavonoids, which have antimicrobial properties (Khan *et al*., 2023). This activation of plant defense pathways enables crops to resist pathogen attack more effectively.

8.7 Integration with biocontrol agents and sustainable disease management

The integration of phytonanotechnology with biological control agents offers a sustainable approach to disease management. Nanoparticles can enhance the effectiveness of beneficial microorganisms such as *Trichoderma* and *Pseudomonas* species by improving their survival and activity. This combined approach reduces reliance on chemical pesticides and promotes eco-friendly crop protection strategies. The synergy between nanoparticles and biocontrol agents represents a promising direction for sustainable agriculture and integrated disease management (Nair *et al*., 2023).

9. Influence on tuber quality and phytochemical composition

Phytonanotechnology not only enhances crop productivity but also plays a crucial role in improving the quality and nutritional composition of potato tubers. Tuber quality is determined by several factors, including starch content, dry matter accumulation, micronutrient composition and the presence of bioactive compounds such as phenolics and antioxidants. The application of phyto-engineered nanoparticles has been shown to influence these parameters by modulating physiological and biochemical processes within the plant. Recent studies indicate that nanoenabled interventions can enhance nutrient assimilation, metabolic activity and secondary metabolite production, thereby improving both the nutritional and functional quality of potato tubers (Kumar *et al*., 2023; Rahman *et al*., 2024). The effects of nanoparticles on starch content and dry matter accumulation are particularly significant, as these parameters directly influence processing quality and consumer preference. Nanoparticles such as zinc oxide and silicon have been reported to enhance carbohydrate metabolism by improving photosynthetic efficiency and enzymatic activity, leading to increased starch synthesis and accumulation in tubers (Rahman *et al*., 2024). Enhanced dry matter content improves the texture, storage stability and suitability of potatoes for processing into chips and fries. Additionally, improved source-sink dynamics facilitated by nanoparticles ensure efficient translocation of assimilates from leaves to tubers, further contributing to higher starch content and better quality.

Biofortification of potato tubers with essential micronutrients such as iron (Fe) and zinc (Zn) is another important application of phytonanotechnology. Micronutrient deficiencies, often referred to as "hidden hunger," are a major global health concern, particularly in developing countries. Nano-enabled nutrient delivery systems can significantly enhance the uptake and accumulation of micronutrients in edible plant parts. Studies have demonstrated that the application of Zn and Fe nanoparticles increases their concentration in potato tubers, thereby improving their nutritional value (El-Saadony *et al*., 2023). This approach offers a sustainable strategy for addressing micronutrient deficiencies without altering dietary habits. Phytonanotechnology also influences the production of phenolic compounds and antioxidants in potato tubers. Phenolics are important secondary metabolites that contribute to the antioxidant capacity and health-promoting properties of potatoes. Nanoparticles have been shown to stimulate the biosynthesis of phenolics by activating key enzymes involved in secondary metabolism, such as phenylalanine ammonia-lyase (PAL). This results in increased antioxidant activity, which enhances the nutritional and functional value of potato tubers (Singh *et al*., 2022). Additionally, improved antioxidant levels help protect tubers from oxidative damage during storage, thereby maintaining quality. Post-harvest quality and storage stability are critical aspects of potato production, as significant losses can occur due to sprouting, microbial spoilage and physiological deterioration. Phytoengineered nanoparticles offer promising solutions for improving post-harvest management by enhancing tuber shelf life and reducing spoilage. Nanocoatings and nano-based treatments have been shown to reduce respiration rates, delay sprouting and inhibit microbial growth on stored tubers (Patel *et al*., 2023). These treatments help maintain tuber firmness, reduce weight loss and preserve nutritional quality during storage. Furthermore, the antimicrobial properties of nanoparticles contribute to effective control of post-harvest pathogens, thereby reducing losses and improving marketability.

10. Challenges and limitations

Despite the promising potential of phytonanotechnology in agriculture, several challenges and limitations hinder its widespread adoption. One of the primary constraints is the lack of large-scale field validation. Most studies on nanoparticle applications have been conducted under controlled laboratory or greenhouse conditions, which may not accurately represent field environments. Variability in soil type, climate and management practices can significantly influence the performance of nanoparticles, making it essential to conduct long-term field trials to validate their effectiveness and safety (Rastogi *et al*., 2022). Another major challenge is the lack of standardization in nanoparticle synthesis, characterization and application protocols. Variations in particle size, shape, concentration and surface properties can lead to inconsistent results, making it difficult to establish uniform guidelines for their use. Additionally, regulatory frameworks for the use of nanoparticles in agriculture are still evolving and there is a need for comprehensive risk assessment to address concerns related to environmental and human health safety (Kah *et al*., 2023). The absence of clear regulations and guidelines poses a barrier to commercialization and adoption by farmers. Economic feasibility and scalability are also critical factors influencing the adoption of phytonanotechnology. Although, green synthesis methods are cost-effective at the laboratory scale, scaling up production for commercial applications remains a challenge. The cost of nanoparticle production, formulation and application may be prohibitive for smallholder farmers, particularly in developing countries. Therefore, developing low-cost and scalable production methods is essential for ensuring the accessibility and adoption of this technology (Verma *et al*., 2024). Furthermore, there are significant knowledge gaps regarding the long-term impacts of nanoparticles on soil health, plant systems and the environment. The accumulation and persistence of nanoparticles in soil and plant tissues may have unintended consequences on soil microbial communities and ecosystem functions. Additionally, the potential transfer of nanoparticles through the food chain raises concerns about human health and food safety. Addressing these knowledge gaps through comprehensive research and risk assessment is crucial for the safe and sustainable use of phytonanotechnology (Nair *et al*., 2023).

11. Future perspectives

The future of phytonanotechnology in agriculture lies in the development of advanced and integrated approaches that enhance efficiency, sustainability and resilience. One of the key areas of advancement is the development of smart nano-delivery systems that can respond to environmental cues such as soil moisture, pH and plant nutrient status. These systems enable precise and controlled release of nutrients and agrochemicals, ensuring optimal utilization and minimal losses. Such innovations are expected to revolutionize nutrient management and crop protection strategies. Integration of phytonanotechnology with precision agriculture technologies is another promising direction. The use of sensors, drones and satellite-based monitoring systems can facilitate real-time assessment of crop health and nutrient status, enabling site-specific application of nanoenabled inputs. This approach enhances resource use efficiency and reduces environmental impact, aligning with the principles of sustainable agriculture. The development of multi-functional nanoparticles capable of performing multiple roles, such as nutrient delivery, disease control and stress mitigation, represents another important research direction. These nanoparticles can be engineered to combine various functionalities, thereby reducing the need for multiple inputs and simplifying crop management practices. Additionally, advances in nanotechnology are enabling the design of nanoparticles with enhanced specificity and efficiency. Omics-based approaches, including genomics, proteomics and metabolomics, offer new insights into the mechanisms underlying nanoparticle–plant interactions. These approaches can help identify key genes, proteins and metabolic pathways involved in nanoparticle-mediated responses, providing a deeper understanding of their mode of action. This knowledge can be used to optimize nanoparticle design and application strategies for improved crop performance. Finally, the development of supportive policy frameworks and commercialization strategies is essential for the successful adoption of phytonanotechnology. Governments and regulatory bodies need to establish clear guidelines for the safe use of nanoparticles in agriculture, including risk assessment and monitoring protocols. Collaboration between researchers, industry stakeholders and policymakers will be crucial for translating research findings into practical applications. With continued innovation and investment, phytonanotechnology has the potential to transform agricultural systems and contribute to global food security in a sustainable manner.

12. Conclusion

Phytonanotechnology has emerged as a promising and sustainable approach for improving potato (*S. tuberosum*) production by integrating green nanomaterials with crop management practices. Recent advancements demonstrate its significant role in enhancing tuber yield, improving nutrient use efficiency (NUE) and strengthening tolerance to both abiotic and biotic stresses. Nano-enabled systems facilitate precise nutrient delivery, promote physiological efficiency and enhance plant defense mechanisms, leading to improved productivity and tuber quality. However, the successful adoption of this technology requires careful consideration of environmental safety, standardization of application protocols and comprehensive risk assessment. Ensuring eco-friendly synthesis and minimizing potential toxicity are essential for long-term sustainability. Future research should focus on large-scale field validation, development of smart nanodelivery systems and integration with precision agriculture. With appropriate regulatory support and technological advancements, phytonanotechnology holds great potential to revolutionize sustainable potato cultivation and contribute to global food security.

Availability of data and material

All data are provided within the manuscript.

Authorship contribution statement

M. Kabilan: Supervision, academic oversight and overall monitoring of the research work; **K. Sundharaiya:** Conceptualization, supervision, critical review and overall guidance of the manuscript; **T. Anitha:** Software handling, reference management, data organization and visualization of the review content; **M. Jayakumar:** Literature survey, data curation and critical analysis of published studies; **Adnan A. Khan:** Critical review, validation of scientific content and final approval of the manuscript.

Consent for publication

All authors gave their full consent for publication and submission to this journal.

Conflict of interest

The authors declare no conflicts of interest relevant to this article.

Funding

The authors stated that the work presented in this article received no associated funding.

Ethics approval

Not applicable.

Acknowledgements

The authors express their gratitude and credit the researchers behind the original studies whose works are referenced in this review.

References

Ahmed, S.; Saifullah; Ahmad, M.; Swami, B. L. and Ikram, S. (2016). Green synthesis of silver nanoparticles using plant extracts and their antimicrobial activities: A review. Journal of Advanced Research, 7(1):17-28.

Beals, K. A. (2019). Potatoes, nutrition and health. American Journal of Potato Research, 96(2):102-110.

Devaux, A.; Kromann, P. and Ortiz, O. (2021). Potatoes for sustainable global food security. Potato Research, 64(1):1-16.

Dimkpa, C. O. and Bindraban, P. S. (2018). Nanofertilizers: New products for the industry. Journal of Agricultural and Food Chemistry, 66(26):6462-6473.

El-Ramady, H.; Abdalla, N.; Taha, H. S.; Alshaal, T.; El-Henawy, A.; Faizy, S. E. D. A. and Shams, M. S. (2022). Nanotechnology and sustainable agriculture: Recent advances and future perspectives. Plants, **11(3)**:345.

El-Saadony, M. T.; Saad, A. M.; Soliman, S. M. and El-Tahan, A. M. (2023). Biofortification of crops using nanotechnology: A sustainable approach. Environmental Science and Pollution Research, **30(12)**:34567-34582.

Fry, W. E.; Birch, P. R. J.; Judelson, H. S.; Grünwald, N. J.; Danies, G.; Everts, K. L. and Ristaino, J. B. (2015). Five reasons to consider Phytophthora infestans a reemerging pathogen. Phytopathology, **105(7)**:966-981.

Hafez, E. M.; Alsohim, A. S.; Farig, M.; Omara, A. E. D.; Rashwan, E.; Kamara, M. M. and Abdelaal, K. A. A. (2024). Green synthesis of nanoparticles and their applications in sustainable agriculture. Communications in Soil Science and Plant Analysis, **55(4)**:567-582.

Hasanuzzaman, M.; Bhuyan, M. H. M. B.; Zulfiqar, F.; Raza, A.; Mohsin, S. M.; Mahmud, J. A. and Fotopoulos, V. (2020). Reactive oxygen species and antioxidant defense in plants under abiotic stress. Antioxidants, **9(8)**:681.

Kah, M.; Kookana, R. S.; Gogos, A. and Bucheli, T. D. (2018). A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. Nature Nanotechnology, **13(8)**:677-684.

Kah, M.; Tufenkji, N. and White, J. C. (2023). Nano-enabled strategies for sustainable agriculture. Nature Food, **4(2)**:123-135.

Khan, I.; Saeed, K. and Khan, I. (2023). Nanoparticles: Properties, applications and toxicities. Arabian Journal of Chemistry, **16(2)**:104623.

Khot, L. R.; Sankaran, S.; Maja, J. M.; Ehsani, R. and Schuster, E. W. (2012). Applications of nanomaterials in agricultural production and crop protection. Crop Protection, **35**:64-70.

Kumar, R.; Kumari, S. and Kumar, V. (2022). Nano-fertilizers and their role in sustainable agriculture. Journal of Plant Nutrition, **45(10)**:1500-1515.

Kumar, S.; Meena, R. S. and Yadav, G. S. (2023). Nanotechnology in agriculture: Opportunities and challenges. Environmental Technology and Innovation, **31**:103148.

Kumar, V.; Singh, J. and Kumar, P. (2025). Advances in nano-enabled agriculture and plant stress management. Environmental Nanotechnology, Monitoring and Management, **23**:100897.

Mgadi, N.; Mthembu, M. S. and Nxumalo, E. N. (2024). Green nanotechnology in agriculture: A sustainable approach. Frontiers in Microbiology, **15**:1354440.

Nair, R.; Varghese, S. H.; Nair, B. G.; Maekawa, T.; Yoshida, Y. and Kumar, D. S. (2023). Nanoparticles in plant systems: Uptake, translocation and effects. Environmental Chemistry Letters, **21(1)**:123-145.

Patel, D.; Singh, R. and Kumar, A. (2023). Nano-based post-harvest technologies for improving crop storage and shelf life. Postharvest Biology and Technology, **198**:112345.

Patel, R.; Sharma, P. and Yadav, S. (2024). Nanotechnology-based approaches for plant disease management. Plant Pathology Journal, **40(2)**:101-115.

Rahman, M. M.; Hossain, M. A. and Islam, M. S. (2024). Nanotechnology in crop production: Enhancing yield and quality. Agronomy, **14(2)**:256.

Rai, M. and Ingle, A. (2012). Role of nanotechnology in agriculture with special reference to management of insect pests. Applied Microbiology and Biotechnology, **94(2)**:287-293.

Rai, M.; Ribeiro, C.; Mattoso, L. and Duran, N. (2015). Nanotechnologies in food and agriculture. Springer International Publishing.

Rai, P. K.; Lee, S. S.; Zhang, M.; Tsang, Y. F. and Kim, K. H. (2021). Heavy metals in food crops: Health risks and mitigation strategies. Environmental Research, **196**:110915.

Raliya, R.; Saharan, V.; Dimkpa, C. and Biswas, P. (2018). Nanofertilizer for precision and sustainable agriculture. Journal of Agricultural and Food Chemistry, **66(26)**:6487-6503.

Rastogi, A.; Tripathi, D. K.; Yadav, S.; Chauhan, D. K.; Živèák, M.; Ghorbanpour, M. and Brestic, M. (2022). Application of nanoparticles in agriculture. Plant Physiology and Biochemistry, **170**:1-12.

Shang, Y.; Hasan, M. K.; Ahammed, G. J.; Li, M.; Yin, H. and Zhou, J. (2021). Applications of nanotechnology in plant growth and crop protection. Environmental Science: Nano, **8(1)**:202-224.

Singh, J.; Dutta, T.; Kim, K. H.; Rawat, M.; Samddar, P. and Kumar, P. (2018). 'Green' synthesis of metals and their oxide nanoparticles: Applications for environmental remediation. Journal of Nanobiotechnology, **16(1)**:84.

Singh, P.; Sharma, V. and Singh, R. (2022). Nanoparticles and plant secondary metabolism: Implications for crop improvement. Plant Cell, Tissue and Organ Culture, **150(2)**:345-360.

Singh, R.; Kumar, A. and Sharma, S. (2023). Antimicrobial mechanisms of nanoparticles in plant disease management. Journal of Applied Microbiology, **134(5)**:1-13.

Singh, S.; Kumar, V. and Meena, R. (2024). Advances in phytonanotechnology for sustainable agriculture. Environmental Research, **240**:117456.

Tripathi, D. K.; Singh, S.; Singh, V. P.; Prasad, S. M.; Chauhan, D. K. and Dubey, N. K. (2023). Silicon nanoparticles in plant stress tolerance. Plant Physiology Reports, **28(1)**:45-60.

Verma, S.; Kumar, P. and Yadav, S. (2024). Nanotechnology for climate-resilient agriculture. Journal of Cleaner Production, **420**:138456.

Zulfiqar, F.; Ashraf, M. and Akram, N. A. (2023). Nanotechnology in agriculture: Current status and future perspectives. Science of the Total Environment, **857**:159661.

Zaman, M.; Shahid, M. and Naeem, M. (2025). Green synthesis of nanoparticles and their role in sustainable crop production. Plants, **14(5)**:716.

Citation **M. Kabilan, K. Sundharaiya, T. Anitha, M. Jayakumar and Adnan A. Khan (2026). Phytonanotechnology in potato (*Solanum tuberosum* L.): Advances in tuber yield, nutrient use efficiency and stress tolerance. J. Phytonanotech. Pharmaceut. Sci., 6(1):11-20. http://dx.doi.org/10.54085/jpps.2026.6.1.2**