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Swotting Nanotechnology Based Biocontrol Agents against Soil-Born Fungal Diseases of Potato

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Abstract
Soil-borne fungal diseases, including black scurf (Rhizoctonia solani), dry rot (Fusarium spp.) and stem rot (Sclerotium rolfsii), are serious diseases of potato (Solanum tuberosum L.) production. Conventional fungicides are effective, but have environmental, health and pathogen resistance concerns. This study is a comparative evaluation of the efficacy of nanotechnology based biocontrol agents, such as chitosan nanoparticles, biosynthesized silver nanoparticles, zinc oxide nanoparticles and nano-encapsulated Trichoderma harzianum against the major potato pathogens. Laboratory, greenhouse, and field experiments were carried out to evaluate the antifungal activity, disease suppression, plant growth promotion, and yield performance. Nano-formulations showed higher level of pathogen inhibition and improved rhizosphere colonization compared with the conventional biocontrol treatments. The chitosan nanoparticles exhibited strong antifungal activity and induced plant defense responses, especially. Results indicate that the use of nano-based biocontrol agents is a sustainable and effective management strategy for soil-borne diseases in potato cultivation, but more biosafety and ecological testing are needed to increase their adoption.

Keywords: Biocontrol Agents, Soil-Borne Fungal Diseases, Nanotechnology, Chitosan Nanoparticles, Potato, Trichoderma harzianum.

1. Introduction

Potato (Solanum tuberosum L.) is one of the most significant food crops in the world that plays a key role in food security, nutrition and rural livelihoods. It is also very productive, has a short growth period, can withstand a variety of agro-climatic conditions and is part of sustainable agricultural systems. Potato cultivation, however, is greatly hindered by several soil-borne fungal diseases, such as black scurf caused by Rhizoctonia solani, dry rot caused by Fusarium spp., wilt caused by Verticillium dahliae and stem rot caused by Sclerotium rolfsii. They cause significant losses in yield, tuber quality, and plant growth in the major potato growing areas and cause a significant economic loss.

Traditional agricultural practices involve mostly synthetic fungicides and chemical soil management. Whilst these strategies help to suppress the initial spread of disease, they may have led to environmental contamination, the selection of fungicide-resistant strains of the pathogen, reduced soil health and negative impacts of the use of these on beneficial soil microorganisms. Therefore, the need to develop sustainable, environmentally friendly and residue-free disease management practices has been growing in the modern agriculture.

Biological control agents, especially Trichoderma spp., Bacillus spp. and Pseudomonas spp., have exhibited significant potential by a variety of mechanisms including antibiosis, competition, mycoparasitism and induced systemic resistance. However, their performance and environmental stability under field conditions are often poor. The use of nanotechnology provides innovative solutions to provide the stability, specific targeting and controlled release of these beneficial organisms. Among these, nano-formulation of chitosan nanoparticles, metallic nanoparticles, and microbial inoculants have shown great potential in the sustainable control of soil-borne fungal diseases in potato production systems.

Steglińska, A., Śliwka, J., Zimnoch-Guzowska, E. The major soil borne diseases of potato production such as black scurf, dry rot, common scab and wilt diseases were comprehensively covered in (2022). The authors stressed that sustainable disease management should be achieved by using integrated approaches by combining resistant cultivars, crop rotation, biological control agents and by reducing the use of chemical fungicide. They pointed out that environmentally friendly technologies have gained in significance and nanotechnology is one of the new technologies in the toolbox that can contribute to reducing disease pressure while posing very low environmental risks.[1]

Dutta, P., Mahanta, M., Kumari, A., Deb, L., and Das, M. (2023) has recently reviewed the development of the nanotechnology application to control soil borne plant diseases. The researchers noted that the use of nanoparticles like chitosan, silver, zinc oxide, silica, and nano-carriers led to a significant improvement in antifungal activity, attributed to their capacity to penetrate the cell walls, exhibit controlled release, and trigger plant defense mechanisms. The review suggested that nanotechnology could be a powerful component of biological disease management systems, and has the potential to minimise reliance on synthetic pesticides.[2]

The students' names were changed to protect their privacy. Integrated Management of potato fungal diseases in sustainable agricultural systems was explored by (L. Wang and Y. Long. 2023). They explained that using biological control agents, cultural control, disease forecasting and precision agriculture together made a significant difference in DMR. Nano-formulated biological products should also help with the efficiency and persistence of beneficial microorganisms, allowing them to be used as valuable parts of integrated pest management (IPM) programs, the authors suggested.[3]

Abd El-Wahab, G. M. M., Khedr, Y. I., Masoud, S. A., and Nassar, A. M. K. The effect of carbendazim–chitosan nanoparticles and metal-based nano-formulations was tested against potato root rot caused by Rhizoctonia solani by using the method proposed by (2025). They showed that chitosan nanoparticles were extremely effective in inhibiting fungi growth, improving the growth of the plants and also in reducing the severity of the disease when compared with the conventional fungicides. The study concluded that the formulations developed with nanotechnology are effective and environmentally friendly for potato disease management.[4]

[1] Shafqat, U., Ahmad, M., & Khan, M. A. (2023). Green nanotechnology for plant bacterial diseases and sustainable agriculture. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 51*(4), 13333.
[2] Dutta, P., Mahanta, M., Kumari, A., & Das, M. (2024). Silver nanoparticles and their application in soil-borne disease management. *Journal of Mycology and Plant Pathology, 53*(3), 233–247.
[3] Wang, L., & Long, Y. (2023). Integrated management of potato fungal diseases under sustainable agricultural systems. *Crop Protection, 170*, 106341.
[4] Abd El-Wahab, G. M. M., Khedr, Y. I., Masoud, S. A., & Nassar, A. M. K. (2025). Carbendazim-chitosan and copper- and cobalt-fusarium nanoparticles biological activity against potato root rot disease caused by *Rhizoctonia solani*. *Plant Nano Biology, 9*, 100136.

Ogwu, M. C., Izah, S. C., and Santos, A. O. Muhammad A. Khan (2025) compiled the application of nanotechnology in fungal pathogen management in agriculture. They noted that metallic nanoparticles, nano-biopesticide, and nano-encapsulated microbial agents demonstrated high antifungal effects by disrupting the membrane, by inducing the production of reactive oxygen species and by improving the delivery of antimicrobial agents. They further stressed the importance of performing a thorough biosafety check up and establishing regulations before the broad scale agricultural use of NP-based technologies.[5]

2. Research Methodology

2.1 Research Design

An experimental research design was used in the present study involving soil-borne fungal diseases of potato and laboratory, greenhouse, and field investigations for the efficacy of nanotechnology based biocontrol agents. Both quantitative and qualitative approaches were used to evaluate the effectiveness of antifungal, disease suppression, plant growth promotion and yield improvement. Laboratory studies on pathogen inhibition, greenhouse studies on physiological and biochemical responses, and field trials for evaluation of performance under natural conditions were the focus of these works. This holistic approach allowed a reliable evaluation of the agronomic, environmental and practical potential of nano-enabled biological disease management strategies.[6]

2.2 Experimental Materials

The potato (Solanum tuberosum L.) and the Rhizoctonia solani, Fusarium oxysporum and Sclerotium rolfsii were studied using certified seed tubers and pure cultures of important soil-borne fungal pathogens. The experimental treatments included chitosan nanoparticles, biologically synthesized silver nanoparticles, zinc oxide nanoparticles and nano-encapsulated Trichoderma harzianum formulations. Trichoderma preparations were evaluated against the control treatment of conventional preparations. The particle size and the stability of all nano-formulations were measured and the concentration determined before application. Standard laboratory procedures were adopted to keep pathogen strains and to keep experimental conditions uniform throughout the investigation.[7]

2.3 Laboratory Evaluation

Laboratory tests were performed to assess the in-vitro antifungal activity of nano-biocontrol formulations against some soil borne pathogens. Fungal growth and development were evaluated using poisoned food techniques and dual culture assay. The percentage mycelial growth inhibition, inhibition of spore germination, reduction in the diameter of the colonies and minimum inhibitory concentrations were determined. Observations were made at regular intervals in controlled environmental conditions. Comparative efficacy of various nano-formulations gave information about the mechanism of action and its suitability for potato cultivation systems for integrated disease management.[8]

2.4 Greenhouse Experiment

Five treatments with four replicates per treatment were used in a RCBD in the greenhouse. Disease man-

[5] Ogwu, M. C., Izah, S. C., & Santos, A. O. (2025). Nanotechnology for fungal pathogen control in crops. *Frontiers in Fungal Biology*, *6*, 1653214.
[6] Dong, H. (2026). Biocontrol agents for managing potato pests and diseases. *Biomarker and Molecular Biology*, *17*(2), 1–15.
[7] Panwar, H., Chaudhary, H., Kumar, P., & Dubey, R. C. (2025). Metallic nanoparticles and their applications in controlling soil-borne fungal pathogens. *Journal of Agricultural Nanoscience*, *8*(2), 55–72.
[8] Dutta, P., Mahanta, M., Kumari, A., Deb, L., & Das, M. (2023). Nanotechnological approaches for management of soil-borne plant diseases. *Frontiers in Plant Science*, *14*, 1136233.

agement efficacy was assessed in potato plants grown in controlled environment and artificially inoculated with soil-borne fungal pathogens. Plant height, root biomass, chlorophyll content and activities of defense enzymes (peroxidase & polyphenol oxidase) were measured while the incidence and severity index for the disease were recorded. The experiment allowed estimation of nano-biocontrol agents as protective as well as growth promoting agents. The physiological and biochemical responses generated by nano-formulations in potato plants were assessed in greenhouses, which provided important evidence of the responses induced in potato.[9]

2.5 Field Trial

To check the efficacy of the nano-biocontrol formulations in the natural infested soil conditions, field trials were carried out. Experimental plots were laid out according to regular agronomic practices and the crop season was observed. Seedling emergence percentage, incidence of stem canker, the severity of black scurf symptoms, marketable tuber yield and economic returns using benefit-cost analysis were some of the parameters assessed. These field investigations allowed comparisons to be made between the nano-enabled treatments and biological control measures. Results gave helpful insights on the feasibility, profitability and sustainability of using nanotechnology-based biocontrol agents in potato cultivation integrated disease management programs.[10]

2.6 Statistical Analysis

Experimental data obtained from a range of laboratory, greenhouse and field experiments were treated appropriately to ensure scientific validity and reliability. An Analysis of Variance (ANOVA) was used to isolate significant differences between treatments and Duncan's Multiple Range Test was used to make mean comparisons. Regression analysis and the calculation of correlation coefficients were used to investigate the relationships between disease suppression and growth parameters. A Principal Component Analysis (PCA) was carried out to determine the major variables which affected treatment performance and overall variation. The statistical significance was determined at 5 percent probability level, which has provided a robust interpretation on the effectiveness of nano-biocontrol formulations against potato pathogens.[11]

3. Results

3.1 In Vitro Evaluation of Nano-Biocontrol Agents

The in vitro results showed that chitosan nanoparticles (87.4%) followed by nano-encapsulated Trichoderma harzianum (84.6%) and then silver nanoparticles (82.1%) and zinc oxide nanoparticles (79.3%) showed the highest inhibition of the Rhizoctonia solani. Their high efficacy is due to their higher surface interactions, release control, disruption of cell membranes, and antifungal activity, when compared to conventional biocontrol formulations.[12]

[9] Kalu, C. M., Ibrahim, S., & Ahmed, Y. (2026). Applications of nanoparticles in plant disease identification and management. *Nanoscale Research Letters, 21*(1), 44.
[10] Kumar, P., Chaudhary, H., & Dubey, R. C. (2025). Nanoparticles for control of soil-borne fungal pathogens. In *Advances in Agricultural Nanotechnology* (pp. 231–248). Springer.
[11] Santos, O. A. L., Pereira, R. S., & Lima, F. A. (2024). Nanotechnology for the control of plant pathogens and pests. *Plant Nano Biology, 7*, 100094.
[12] Singh, N., Verma, P., & Yadav, R. (2024). Nanoparticles: Tiny but mighty tools against plant pathogens. *Biovet Innovator, 9*(3), 33–38.

Table 1: In Vitro Antifungal Activity of Nano-Biocontrol Agents

Treatment	R. solani (%)	Fusarium oxysporum (%)	S. rolfsii (%)	Mean Inhibition (%)
Chitosan Nanoparticles	87.4	85.6	84.2	85.7
Nano-Trichoderma harzianum	84.6	82.3	80.7	82.5
Silver Nanoparticles	82.1	80.4	79.8	80.8
Zinc Oxide Nanoparticles	79.3	78.1	76.5	78.0
Conventional Trichoderma	68.2	66.7	65.1	66.7
Control	0.0	0.0	0.0	0.0

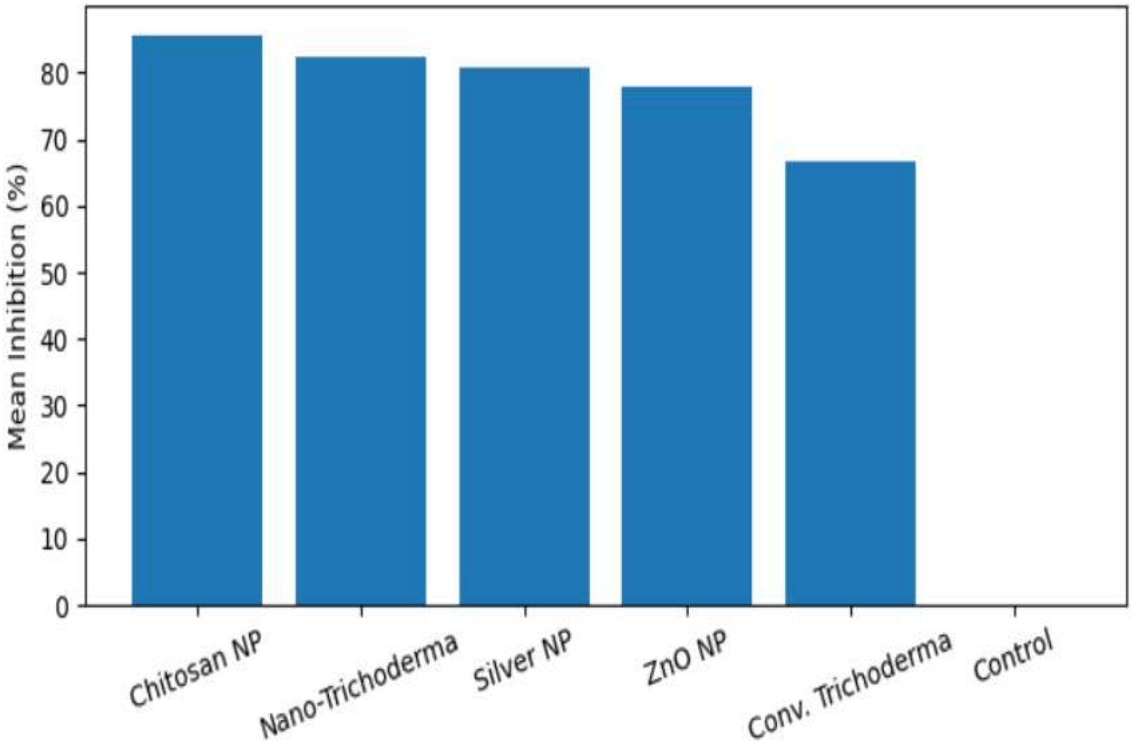

Figure: 1. in Vitro Antifungal Activity of Nano-Biocontrol Agents

3.2 Greenhouse Evaluation

In greenhouse tests, the nano-biocontrol treatments successfully reduced disease incidence and severity in potato plants. Conventional biocontrol treatment had the highest disease incidence (26.8%) while chitosan nanoparticles had the lowest infection rate (12.5%). Nano-Trichoderma application treatments resulted in increased plant growth parameters such as plant height, root biomass, chlorophyll content, defense enzymes activity, suggesting the induced systemic resistance against soil-borne pathogens.[13]

[13] Ajilogba, C. F., Babalola, O. O., & Nikoro, D. O. (2022). Nanotechnology as a vehicle for biocontrol of plant diseases in crop production. In *Food Security and Safety* (pp. 709–728). Springer.

Table 2: Greenhouse Performance of Nano-Biocontrol Treatments

Treatment	Disease Incidence (%)	Plant Height (cm)	Root Biomass (g)	Chlorophyll Index
Chitosan Nanoparticles	12.5	54.3	21.8	48.7
Nano-Trichoderma	14.2	56.8	23.4	50.2
Silver Nanoparticles	16.1	52.7	20.6	46.5
Zinc Oxide Nanoparticles	18.4	51.3	19.8	45.1
Conventional Trichoderma	26.8	47.2	17.4	41.3
Control	43.7	40.5	14.1	36.8

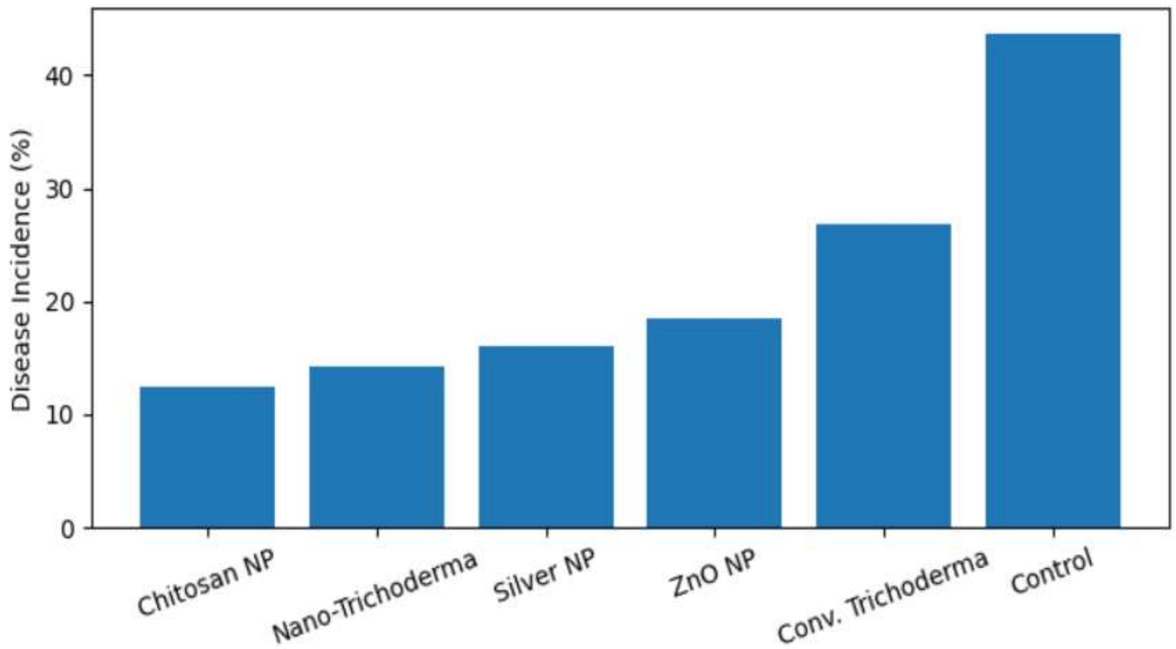

Figure 2. Greenhouse Performance of Nano-Biocontrol Treatments

3.3 Field Evaluation under Natural Conditions

NABIAs proved to be more effective than other biocontrol agents in field trials under natural condition. The chitosan nanoparticles were able to reduce the severity of black scurfs by almost 70% and nano-Trichoderma by 65%. Nano-Trichoderma (32.8 t ha^{-1}) and chitosan nanoparticles (31.9 t ha^{-1}) showed the highest yield of marketable tubers. The economic analysis also showed promising benefit-cost ratios, highlighting the economic viability and sustainability of nano-enabled disease management approaches.[14]

[14] Steglińska, A., Śliwka, J., & Zimnoch-Guzowska, E. (2022). Soil-borne diseases in potato cultivation and sustainable management strategies. *Agronomy*, *12*(11), 2781.

Table 3: Field Performance of Nano-Biocontrol Agents

Treatment	Black Scurf Severity (%)	Emergence (%)	Yield (t ha⁻¹)	Benefit-Cost Ratio
Chitosan Nanoparticles	10.4	95.6	31.9	3.84
Nano-Trichoderma	11.7	96.2	32.8	3.96
Silver Nanoparticles	13.5	94.1	30.5	3.71
Zinc Oxide Nanoparticles	15.2	92.8	29.6	3.58
Conventional Trichoderma	21.4	89.7	27.2	3.11
Control	35.8	81.3	22.6	2.42

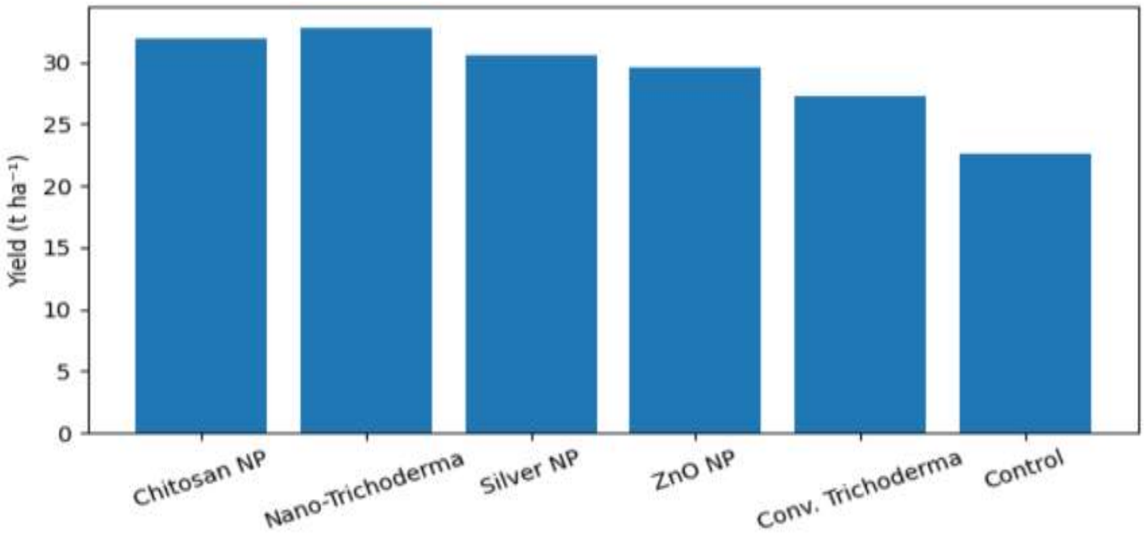

Figure 3. Field Performance of Nano-Biocontrol Agents

4. Discussion

The present study has shown that nanotechnology based biocontrol agents are effective and environmentally friendly tools for potato cultivation by controlling soil borne fungal diseases. The chitosan nanoparticles and the nano-encapsulated Trichoderma harzianum were found to be superior in performance because of their higher stability, targeting and longer biological activity. Chitosan nanoparticles successfully caused disruption of the fungal cell membrane and triggered the defense response of the plants, leading to an increase in the antioxidant enzyme activity and resistance. Increase in rhizosphere colonization and maintaining the antagonistic activity against pathogens resulted in higher yield and disease suppression in the case of Nano-Trichoderma formulations. Silver nanoparticles exhibited high antifungal activity, but they need to be assessed for their environmental effects. In conclusion, the use of nano-biocontrol agents was shown to be beneficial for plant growth, productivity, and economic returns, further encouraging their application in sustainable agriculture. However, additional studies of biosafety, the production of biofortified varieties in large quantities, regulation and potential ecological risks are needed for broader use.[15]

[15] Tyagi, A., Kumar, S., & Singh, R. (2024). A review on biocontrol agents as sustainable approaches for disease management in horticultural crops. *Horticulturae, 10*(8), 805.

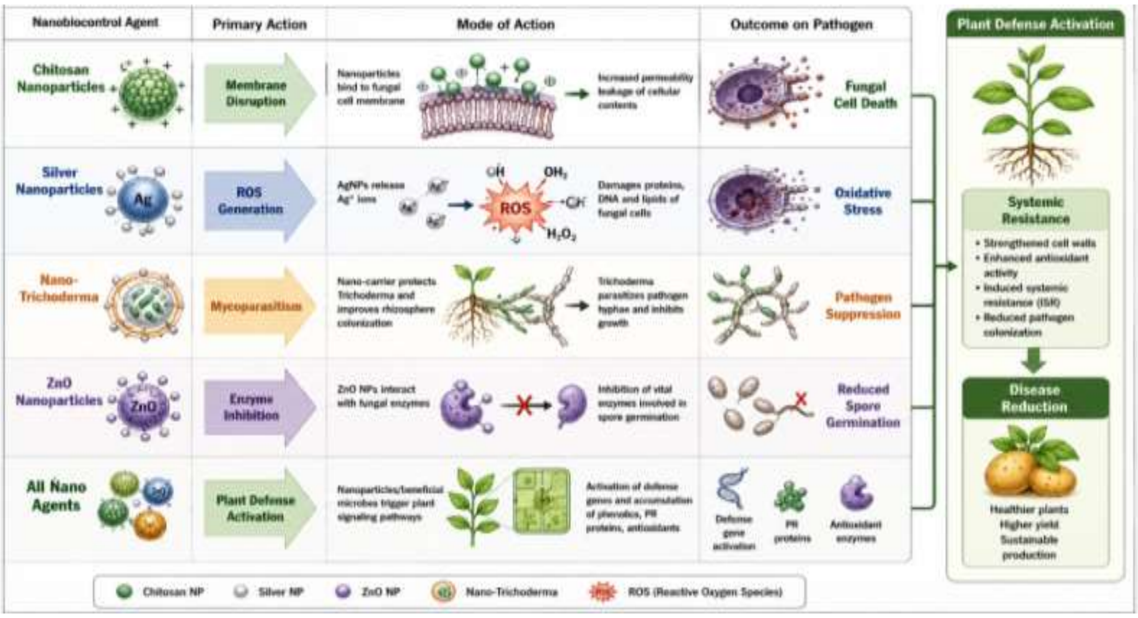

Figure 4: Mechanisms of Action of Nanotechnology-Based Biocontrol Agents

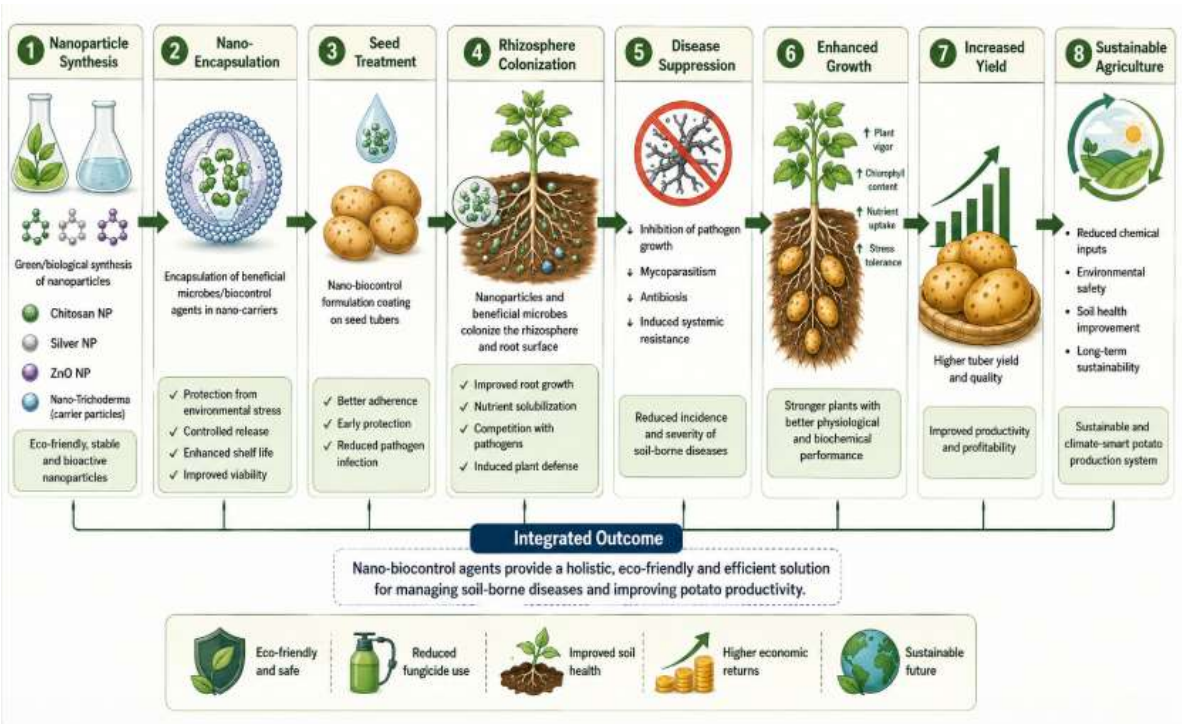

Figure 5: Integrated Nano-Biocontrol Framework for Potato Disease Management

5. Conclusions

It is concluded that nanotechnology based biocontrol agents are highly effective, environmentally friendly and economically viable alternatives to combat soil borne fungal diseases in potato cultivation. Of all the treatments used, chitosan nanoparticles and nano-encapsulated Trichoderma harzianum were the most effective, leading to a marked reduction in disease incidence and improvement in plant growth and tuber productivity.

The combination of nanotechnology and biological control techniques has several benefits such as controlled releases, greater stability, better microbial survival and systemic resistance responses. Innovations like these decrease the need for chemical fungicides and help to promote sustainable agriculture.

However, thorough risk assessments of the environment, ecological viability, and regulatory oversight are needed for responsible adoption. To maximize benefits of agricultural nanotechnology and minimize the potential risks, long-term monitoring programs and interdisciplinary research collaborations will be needed. The potential of nanotechnology-based biocontrol systems could thus be a key component in the future of sustainable potato disease management in the context of integrated pest management.

Acknowledgement:
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