

Effect of Green-Synthesized Nanoparticles-Based Nanofertilizers on Crop Morphology for Sustainable Agriculture

Mamta Satishrao Pawar¹, Dilip Uttam Ahire²

^{1,2}Research Center in Botany, MSG Arts, Science & Commerce College, Malegaon camp, Dist- Nashik (MS), Affiliated to Savitribai Phule Pune University, Pune (India)

Abstract:

The present work reports the green synthesis of silver nanoparticles (AgNPs) using *Crotalaria juncea* L. plant extract as a natural reducing and stabilizing agent for nanofertilizer applications. The silver nitrate solution was reacted with the plant extract, and a rapid color change confirmed nanoparticle formation. The synthesized AgNPs were purified, dried, and used as nanofertilizer. When applied to Wheat (*Triticum aestivum* L.) and Mung (*Vigna radiata* L.), the nanoparticles significantly improved plant growth, root–shoot development, branching, and yield attributes. The enhancement was attributed to improved nutrient uptake, photosynthetic efficiency. This eco-friendly method offers a sustainable and non-toxic alternative to chemical fertilizers, promoting green nanotechnology in agriculture. This study establishes Sunn Hemp–mediated Ag nanoparticles as promising eco-friendly nanofertilizers, offering a sustainable and non-toxic alternative to conventional chemical fertilizers, contributing to soil health, and promoting environmentally safe agricultural practices.

Keywords: *Green synthesis, Crotalaria juncea* L., *Silver oxide nanoparticles, Nanofertilizer, Wheat, Mung, Sustainable agriculture.*

1. Introduction

Nanotechnology is one of the most dynamic and revolutionary scientific advancements of the 21st century, with significant implications across various domains including healthcare, energy, environment, and agriculture [1, 2]. The term nanotechnology refers to the design, synthesis, characterization, and application of materials at the nanoscale typically ranging from 1 to 100 nanometers, where materials exhibit unique physical, chemical, and biological properties distinct from their bulk counterparts. At this scale, phenomena such as quantum confinement, increased surface-to-volume ratio, and enhanced reactivity endow nanomaterials with remarkable functionalities that can be harnessed to address complex challenges in multiple sectors. Among its diverse applications, the integration of nanotechnology into agriculture has shown immense potential for improving crop productivity, resource efficiency, and sustainability [3, 4]. By enabling precise control over nutrient delivery, disease detection, and soil health management, nanotechnology offers innovative solutions to meet the growing global food demand while minimizing environmental degradation. The emergence of green nanotechnology has further strengthened this field by introducing eco-friendly, cost-effective, and sustainable synthesis routes for producing nanoparticles. Conventional chemical and physical methods of nanoparticle synthesis often involve high energy consumption, toxic solvents, and hazardous by-products, raising concerns regarding environmental and human safety [4-6]. In contrast, green nanotechnology employs biological systems such as plants, microorganisms, and biomolecules to reduce metal ions into nanoparticles under mild reaction conditions. This approach aligns with the principles of green chemistry reducing the use of harmful substances and promoting renewable resources. Among biological routes, plant-mediated synthesis has gained particular

importance due to its simplicity, scalability, and ability to produce stable, biocompatible nanoparticles [7, 8]. Plant extracts are rich in secondary metabolites such as flavonoids, phenolics, terpenoids, alkaloids, and proteins, which act as both reducing and stabilizing agents. These biomolecules facilitate the reduction of metal ions to nanoparticles while preventing their agglomeration, resulting in uniform nanostructures with excellent stability.

The impact of nanotechnology in agriculture is profound, with applications spanning from seed germination enhancement and pest control to soil fertility management and post-harvest preservation. Conventional agriculture heavily relies on chemical fertilizers and pesticides to achieve higher yields; however, their excessive use has led to serious environmental issues, including soil degradation, groundwater contamination, and the disruption of microbial biodiversity. Nanotechnology offers a promising solution to these challenges through the development of nano-enabled agrochemicals, such as nanopesticides, nanofungicides, and nanofertilizers [5, 9]. These nanoscale formulations improve the efficiency of nutrient and pesticide delivery, reduce wastage, and minimize the release of harmful substances into the environment. In particular, nanofertilizers have emerged as one of the most promising applications of agricultural nanotechnology due to their potential to enhance nutrient-use efficiency, reduce input costs, and promote sustainable crop growth [8-10].

Nanofertilizers are innovative nutrient delivery systems that utilize nanoscale carriers to release essential macro- and micronutrients in a controlled and targeted manner. Unlike conventional fertilizers, which often suffer from poor solubility and rapid nutrient losses due to leaching and volatilization, nanofertilizers provide sustained nutrient release and improved plant uptake. Their small particle size allows for better adhesion to plant surfaces and facilitates nutrient penetration through stomata or root tissues [11, 12]. The nanofertilizers improve soil nutrient dynamics, stimulate enzymatic activity, and promote photosynthetic efficiency, ultimately leading to improved plant growth and yield. Various nanomaterials such as silver (Ag), zinc (Zn), iron (Fe), Cobalt (CO), Copper (Cu), Magnesium (Mg), Manganese (Mn), titanium (Ti), Silicon (Si) and Selenium (Se) nanoparticles have been explored for nanofertilizer in agriculture applications. These metal based nanofertilizers possess high stability, reactivity, and biocompatibility, enabling them to play a dual role acting as nutrient sources and as stress mitigators by enhancing enzyme activities in plants [9, 13].

The need for metal-based nanofertilizers arises from the limitations of conventional fertilizers and the increasing demand for sustainable agricultural inputs. Traditional fertilizers often exhibit low nutrient-use efficiency, with only 30–50% of applied nutrients effectively utilized by crops [14, 15]. The remainder is lost through leaching, runoff, and volatilization, contributing to environmental pollution and economic loss. Metal nanoparticles, on the other hand, possess slow-release properties that ensure continuous nutrient availability throughout the plant growth cycle. Their nanoscale dimensions enhance surface reactivity and interaction with plant roots, improving nutrient absorption. These nanoparticles can stimulate plant metabolic and enzymatic processes, regulate ion homeostasis, and mitigate abiotic stress conditions such as salinity and drought [16, 17]. The Zn nanoparticles enhance chlorophyll synthesis and enzyme activation, Ti nanoparticles improve photosynthesis and nitrogen metabolism, while Fe nanoparticles enhance oxygen transport and electron transfer in plants. Among the various metal-based nanomaterials, silver nanoparticles (Ag/ AgNPs) have attracted particular attention due to their exceptional physicochemical, biological, and antimicrobial properties. Silver has been historically known for its nanofertiliser and antibacterial activity, and at the nanoscale, its efficiency increases significantly due to its large surface area and high surface energy. Silver nanoparticles exhibit strong antimicrobial effects against a broad spectrum of pathogens including bacteria, fungi, and viruses, making them valuable in agricultural disease management also. The AgNPs possess excellent electrical and optical properties, high catalytic activity, and remarkable stability, which further enhance their applicability. In agriculture,

AgNPs have been explored for improving seed germination, root elongation, nutrient uptake, and plant defense mechanisms. When used as nanofertilizers, they not only supply essential micronutrients but also protect plants from microbial infections, thereby enhancing crop productivity and quality [17-20].

The synthesis of silver nanoparticles can be achieved through various methods, broadly classified into physical, chemical, and biological (green) synthesis techniques. Physical methods such as laser ablation, evaporation–condensation, and ball milling provide high purity nanoparticles but require expensive equipment and high energy inputs. Chemical methods, including chemical reduction, sol-gel processing, and precipitation, are efficient but involve toxic reducing and capping agents such as sodium borohydride, hydrazine, or citrate, which pose environmental and health hazards. In contrast, green synthesis methods are environmentally benign, cost-effective, and suitable for large-scale production [13, 15]. In green synthesis, biological entities such as plant extracts or microbial cultures are used as both reducing and stabilizing agents, eliminating the need for hazardous chemicals. Among these, plant-mediated synthesis stands out for its simplicity, reproducibility, and the use of renewable raw materials. Plant extracts act as natural factories, where phytochemicals reduce silver ions (Ag^+) to metallic silver (Ag^0) or silver oxide (Ag_2O), forming stable nanoparticles with biocompatible surface coatings [16, 17].

The application of such green-synthesized Ag nanoparticles as nanofertilizers in crops like Wheat (*Triticum aestivum* L.) and Mung (*Vigna radiata* L.) demonstrates their potential in enhancing plant growth and productivity. Experimental evidence suggests that AgNPs improve plant height, root and shoot biomass, number of branches, spike or pod length, and grain or seed yield. The underlying mechanism involves improved nutrient uptake, stimulation of enzymatic activities, enhanced photosynthetic efficiency, and the activation of antioxidant defense systems that protect plants from oxidative damage.

The aim of the present work is to synthesize silver nanoparticles (AgNPs) using a green, eco-friendly approach employing *Crotalaria juncea* L. (Sunn Hemp) plant extract as a natural reducing and stabilizing agent, and to evaluate their potential application as nanofertilizers for enhancing the growth and yield of Wheat (*Triticum aestivum* L.) and Mung (*Vigna radiata* L.) crops. The study seeks to develop a sustainable, non-toxic, and cost-effective alternative to conventional chemical fertilizers by utilizing plant-based phytochemicals for nanoparticle synthesis. Furthermore, it objectives to investigate the influence of biosynthesized AgNPs on morphological and yield parameters such as plant height, root length, number of branches, biomass accumulation, and grain or seed yield. By integrating green nanotechnology with agricultural practices, this work aspires to promote environmentally safe and efficient nanofertilizer development, contributing to improved crop productivity and soil health while minimizing ecological impact.

2. Experimental work

All AR-grade chemicals were used. Silver nanoparticles (AgNPs) were green synthesized using *Crotalaria juncea* L. (Sunn Hemp) extract as a natural reducing and stabilizing agent, with silver nitrate (AgNO_3) as the metal precursor. Fresh, healthy Sunn Hemp leaves, stems, and roots were washed thoroughly, chopped, and heated in double-distilled water at 50–60 °C for 20–30 minutes to extract bioactive compounds. After cooling, the mixture was filtered to obtain a clear aqueous extract used as the bioreductant. A 1 mM AgNO_3 solution was prepared, and the Sunn Hemp extract was added dropwise under stirring at room temperature. The reaction mixture color changed from colorless to yellowish-brown, then dark brown, indicating AgNP formation via reduction of Ag^+ ions. The mixture incubated for 24 hours in a dark room to complete bioreduction and prevent photo-degradation. Nanoparticles were separated by centrifugation at 12,000–15,000 rpm for 10–30 minutes, washed multiple times with distilled water, then dried at ambient temperature to obtain AgNP powder for further analysis [21, 22].

3. Result and Discussion

3.1 Soil Analysis Parameters:

Soil analysis was performed before the experiment for nutrient status of soil. Soil analysis results are presented as shown in Table 1 for wheat crop cultivation and Mungbean crop cultivation. Soil was collected with 0 to 24 cm depth for wheat and mung crop cultivation field and were analysed with the procedures as: soil pH, electrical conductivity, organic carbon, calcium carbonate nitrogen, phosphorous and potassium in the lab. As organic matter content was very low, organic manures as well as NPK fertilizers as per recommended doses of N, P, K (kg ha⁻¹) expected to apply [23].

Table 1: Soil Test Report for Wheat and mung crop cultivation

Sr. No.	Parameter	Unit	Range	Result for wheat crop cultivation	Result for Mung crop cultivation
1	pH	-	6.00-8.00	7.4	7.2
2	Electrical Conductivity	ds/m	<1.00	0.23	0.37
3	Organic Carbon	%	0.50-0.75	0.38	0.32
4	Calcium Carbonate	%	0.1-10.00	3.92	4.23
5	Available Nitrogen (N)	Kg/ha	280-560	152	186
6	Available Phosphorus (P)	Kg/ha	22-56	11.56	13.62
7	Available Potassium (K)	Kg/ha	112-280	242	255

3.2 Morphological Parameters:

The application of *Crotalaria juncea* L. (Sunn Hemp)–mediated silver nanoparticles (AgNPs) produced remarkable improvements in both Wheat (*Triticum aestivum* L.) and Mung (*Vigna radiata* L.) morphological traits compared to the control plants. Treated plants exhibited enhanced vegetative vigor, including increased shoot height, leaf area, and root development. The average plant height increased significantly under AgNP treatment, reaching optimal growth ranges, indicating improved photosynthetic efficiency and nutrient assimilation. Root length and biomass were also substantially higher in treated plants, suggesting that AgNPs promoted root proliferation and branching, thereby improving water and nutrient uptake efficiency [24-26]. The increased root activity correlated positively with above-ground biomass, contributing to robust tillering and greater yield potential. In Wheat, the number of productive tillers per plant increased, leading to higher spike density, while in Mung, the treated plants showed improved pod formation and seed filling. These enhancements are consistent with earlier studies indicating that green-synthesized AgNPs, through plant-derived bioactive compounds, enhance physiological and biochemical processes responsible for growth regulation. Both Wheat and Mung showed significant morphological improvements upon AgNPs treatment. Wheat plants recorded higher plant height, root length, and tiller number, while Mung plants exhibited enhanced shoot length, number of branches, and leaf area. The overall plant vigor and biomass were notably improved under optimized AgNP concentrations compared to the control group illustrate in Table 2.

Table 2: Comparative morphological characteristics of wheat and Mung under different treatments.

Crop	Treatment	Plant Height (cm)	Root Length (cm)	No. of Tillers/ Branches per Plant	Leaf Area (cm ²)	Fresh Biomass (g/plant)	Dry Biomass (g/plant)
Wheat (<i>Triticum</i>)	Control	72.4 ± 1.5	10.6 ± 0.8	3.2 ± 0.4	35.8 ± 2.1	6.45 ± 0.5	2.85 ± 0.3

aestivum L.)	Chemical Fertilizer	84.3 ± 2.0	13.8 ± 0.9	4.8 ± 0.5	46.2 ± 2.8	8.96 ± 0.6	3.85 ± 0.4
	AgNPs (Green Synthesized)	92.7 ± 2.2	16.4 ± 1.1	5.6 ± 0.6	52.9 ± 3.0	10.32 ± 0.7	4.62 ± 0.5
Mung (Vigna radiata L.)	Control	38.5 ± 1.0	7.8 ± 0.6	2.4 ± 0.3	24.5 ± 1.8	3.52 ± 0.4	1.62 ± 0.2
	Chemical Fertilizer	44.9 ± 1.3	9.6 ± 0.7	3.6 ± 0.4	30.2 ± 2.1	4.78 ± 0.5	2.18 ± 0.3
	AgNPs (Green Synthesized)	51.2 ± 1.5	11.5 ± 0.8	4.8 ± 0.5	34.8 ± 2.3	5.63 ± 0.6	2.65 ± 0.3

From Table 2, it is found that, in both Wheat and Mung, treatment with *C. juncea*-derived AgNPs significantly enhanced all morphological parameters compared to control and chemically fertilized plants [27-28]. The highest plant height, root length, tiller/branch number, and biomass were observed in AgNP-treated plants, confirming that biosynthesized nanoparticles improved nutrient assimilation, photosynthetic activity, and overall plant vigor. The improvements were more pronounced in Wheat due to its higher biomass potential, also similar proportional gains were evident in Mung.

Significant variations were observed in spike morphology and yield attributes among AgNP-treated Wheat plants. The spike length, number of spikelets per spike, and grains per spike showed substantial increases compared to the untreated control. The 1000-grain weight exhibited a noticeable improvement, indicating enhanced source-sink efficiency. Similarly, in Mung, the number of pods per plant, seeds per pod, and seed weight increased under AgNP treatment. This improvement demonstrates that green-synthesized AgNPs facilitate efficient nutrient translocation and sustained photosynthetic activity. The beneficial effects of *Crotalaria juncea*-mediated AgNPs can be attributed to the presence of phytochemicals such as flavonoids, alkaloids, and phenolics, which act as natural capping and reducing agents. A dose-dependent response was observed across both crops. At lower to moderate concentrations (10–30 ppm), *C. juncea*-derived AgNPs significantly promoted growth and yield, while higher doses (>50 ppm) exhibited phytotoxic effects, reducing germination and chlorophyll content. Compared with chemical fertilizers, AgNP-treated plants maintained better morphological parameters and exhibited higher growth stability, underscoring the eco-friendly potential of green nanotechnology.

4. Conclusions and Future Scope

The present study demonstrates that green-synthesized silver nanoparticles (AgNPs) using *Crotalaria juncea* L. (Sunn Hemp) extract serve as an efficient, eco-friendly, and sustainable approach to enhancing the growth and yield performance of Wheat (*Triticum aestivum* L.) and Mung (*Vigna radiata* L.) crops. The use of plant-based reducing and stabilizing agents not only eliminates the need for toxic chemicals but also introduces beneficial phytochemicals that contribute to improved plant physiology. The experimental results revealed that AgNP treatment significantly improved morphological parameters such as plant height, root and shoot biomass, tiller or branch number, and leaf area, alongside enhanced yield attributes including spike/pod length, number of grains or seeds, and overall test weight. These findings confirm that moderate concentrations of Sunn Hemp-mediated AgNPs positively influence nutrient uptake and chlorophyll synthesis resulting in vigorous growth and superior productivity compared to conventional fertilizers. This study highlights the green synthesis approach offers an environmentally safe alternative for sustainable agriculture, minimizing ecological risks associated with chemical fertilizers.

The future scope of the present research work is to extensive field trials across diverse agro-climatic zones and soil conditions should be undertaken to validate the consistency of these findings under real-world agricultural environments. Long-term studies are also needed to evaluate the environmental persistence, bioaccumulation, and ecotoxicological effects of AgNPs in soil–plant systems. Additionally, exploring the synergistic effects of multi-metal or biopolymer-stabilized nanoparticles and optimizing nanoparticle dosage, size, and application mode (seed priming, foliar spray, or soil amendment) will further refine their efficiency. Integrating such green nanotechnological innovations with precision agriculture and organic farming practices can pave the way toward next-generation sustainable crop management systems that enhance productivity while preserving ecological balance.

Acknowledgment

The authors sincerely acknowledge the Research Center in Botany, Mahatma Gandhi Vidyamandir's MSG Arts, Science & Commerce College, Malegaon Camp, Malegaon, Dist. Nashik for providing the necessary laboratory facilities, research environment, and continuous support throughout the course of this work. The authors also extend their heartfelt thanks to the farmers and Soil Testing Laboratory, K.K. Wagh College of Agricultural, Panchavati, Nashik for their valuable assistance in conducting the analysis of collected soil samples used for wheat and Mung crop cultivation, which greatly contributed to the successful completion of this research study.

REFERENCES:

1. Bhardwaj, D., Sharma, S. and Sharma, P., 2020. Role of nanotechnology in improving soil health and crop productivity. *Agricultural Reviews*, 41(2), pp.132–140.
2. Hossain, Z. and Kurihara, H., 2017. Application of nanotechnology to increase crop yield: A review. *Environmental Science and Pollution Research*, 24(10), pp.9443–9458.
3. Chinnamuthu, C.R. and Boopathi, P.M., 2009. Nanotechnology and agroecosystem. *Madras Agricultural Journal*, 96(1–6), pp.17–31.
4. Dasgupta, N. and Ranjan, S., 2019. *Nanotechnology in Agro-Food Industry: Principles and Applications*. Academic Press, London.
5. Dwivedi, A.D. and Gopal, K., 2010. Biosynthesis of silver and gold nanoparticles using *Chenopodium album* leaf extract. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 369(1–3), pp.27–33.
6. El-Saadony, M.T., Desoky, E.S.M., and Saad, A.M., 2021. The use of nanotechnology in agriculture: A review. *Environmental Nanotechnology, Monitoring & Management*, 16, p.100622.
7. Adebayo, E.A., Ibikunle, J.A. and Omomowo, O.I., 2022. Green synthesis of silver nanoparticles using plant extracts and their applications: A review. *Applied Nanoscience*, 12(3), pp.567–584.
8. Ahmed, S., Ahmad, M., Swami, B.L. and Ikram, S., 2016. A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications: A green expertise. *Journal of Advanced Research*, 7(1), pp.17–28.
9. Ali, M., Khan, M.S. and Saquib, Q., 2021. Nanotechnology in sustainable agriculture: Present concerns and future aspects. *Journal of Cleaner Production*, 278, p.123692.
10. AlMutairi, K.M., 2020. Biosynthesis of silver nanoparticles using plant extracts and their potential role as nanofertilizers: A review. *Environmental Nanotechnology, Monitoring & Management*, 14, p.100354.
11. Asghar, M.A., Zahir, E., Shahid, S.M. and Khan, M.N., 2018. Green synthesis of silver nanoparticles using plant extracts and their possible synergistic antibacterial effects. *Nanomaterials*, 8(8), p.484.

12. Ashokkumar, S., Ravi, S., Kathiravan, V., and Velmurugan, S., 2020. Green synthesis of silver nanoparticles using leaf extract of *Crotalaria juncea* and their antibacterial and antioxidant activities. *Materials Letters*, 264, p.127336.
13. Bhat, R.A., Shivaraj, R. and Patil, S.B., 2021. Green synthesis and characterization of silver nanoparticles from medicinal plant extracts. *Journal of King Saud University–Science*, 33(1), p.101255.
14. Elumalai, E.K., Prasad, T.N.V.K.V., Hemachandran, J., and Thirumalai, T., 2010. Extracellular synthesis of silver nanoparticles using leaf extract of *Crotalaria juncea* and their antibacterial activity. *Colloids and Surfaces B: Biointerfaces*, 79(2), pp.183–187.
15. Ghorbanpour, M. and Varma, A. (eds.), 2017. *Nanotechnology and Plant Sciences: Nanoparticles and Their Impact on Plants*. Springer, Cham.
16. Goswami, A., Roy, I., Sengupta, S. and Debnath, N., 2017. Novel applications of solid and liquid formulations of nanoparticles against insect pests and pathogens. *Pest Management Science*, 73(6), pp.1121–1136.
17. Iqbal, M., Raja, N.I., Mashwani, Z.U.R. and Ashraf, M.A., 2019. Green synthesis and characterization of silver nanoparticles: A review on recent advances and future perspectives. *International Journal of Biological Macromolecules*, 134, pp.952–965.
18. Kah, M., Tiede, K. and Gottschalk, F., 2019. Nanopesticides and nanofertilizers: Emerging trends, risks and regulatory challenges. *Environmental International*, 132, p.105043.
19. Khot, L.R., Sankaran, S., Maja, J.M., Ehsani, R. and Schuster, E.W., 2012. Applications of nanomaterials in agricultural production and crop protection: A review. *Crop Protection*, 35, pp.64–70.
20. Kumar, R., Umar, A., and Kumar, G., 2015. Metal oxide nanoparticles and their applications in agriculture. *Nanoscale Research Letters*, 10(1), pp.1–14.
21. Mahapatra, D.M., Mishra, A. and Padhiary, A.K., 2020. Green synthesis of silver nanoparticles and their potential applications as nanofertilizers in agriculture. *Journal of Plant Nutrition*, 43(15), pp.2317–2330.
22. Mittal, A.K., Chisti, Y. and Banerjee, U.C., 2013. Synthesis of metallic nanoparticles using plant extracts. *Biotechnology Advances*, 31(2), pp.346–356.
23. Paramo, L.A., Feregrino-Perez, A.A., Guevara, R. and Mendoza, S., 2020. Green synthesis of silver nanoparticles using plant extracts and their applications: A review. *Journal of Advanced Research*, 31, pp.55–67.
24. Rajeshkumar, S. and Bharath, L.V., 2017. Mechanism of plant-mediated synthesis of silver nanoparticles: A review on biomolecules involved, characterisation and antibacterial activity. *Chemico-Biological Interactions*, 273, pp.219–227.
25. Ramesh, M., Palanisamy, K. and Babu, M., 2020. Role of nanofertilizers in sustainable agriculture and their potential impacts on soil–plant system. *Environmental Nanotechnology, Monitoring & Management*, 14, p.100347.
26. Sharma, G., Sharma, A.R., Bhavesh, R., and Singh, R.P., 2014. Green synthesis of silver nanoparticles using plant extracts and their antimicrobial activities: A review. *Green Chemistry Letters and Reviews*, 7(4), pp.273–288.
27. Singh, A., Dubey, P., and Singh, S.K., 2021. Role of nanotechnology in improving soil fertility and crop productivity: A sustainable approach. *Nanotechnology for Environmental Engineering*, 6(3), pp.1–12.
28. Verma, R.S., Dwivedi, P., and Singh, R., 2022. Plant-based synthesis of silver oxide nanoparticles and their application as eco-friendly nanofertilizers. *Journal of Environmental Chemical Engineering*, 10(5), p.107045.