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Seed Priming with Green Synthesized Nanoparticles

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Seed priming with green-synthesized nanoparticles (NPs) is an emerging technique that can dramatically boost seed germination and early plant growth while using eco-friendly materials. In this approach, plant extracts or agro-waste materials are used to form biocompatible metal (e.g. silver, copper) or metal-oxide (e.g. zinc oxide) nanoparticles. Treated seeds are then imbibed or coated with these NPs before sowing. The result is often faster, more uniform germination and stronger seedlings. Studies show that even under stress conditions (drought, salinity, pathogens), nano-primed seeds outperform unprimed ones, with higher vigour and yields. For example, watermelon seeds primed with onion-extract silver NPs gave 30–35% higher fruit yield. Wheat priming with 40 mg/L plant-made AgNPs lifted germination from 70% to 90% under salt stress, with dramatically longer roots. Such benefits arise because the tiny particles (15–100 nm) improve water uptake, activate key enzymes (like amylases) and trigger mild oxidative signals that "wake up" the embryo. This article explains how green-synthesized NPs are made and used, summarizes key findings in different crops and discusses what this means for farmers and researchers.

Keywords: Seed priming, green-synthesized nanoparicles, silver nanoparticles, germination

Introduction

High-quality seed germination is vital for crop success, yet many seeds still emerge slowly or unevenly. Seed priming is a method of pre-treating seeds before planting. It has long been used to speed up and synchronize germination. Traditional priming methods include soaking seeds in water, nutrients or hormones. More recently, nanopriming has emerged as a powerful twist: it uses nanoparticles to give an extra boost. Nanoparticles are extremely small (billionths of a metre) materials that can carry nutrients or signals into the seed. In particular, green-synthesized nanoparticles use plant extracts (leaves, peels, roots, etc.) to produce the NPs in an eco-friendly way. These plant-based NPs are generally safer and more biodegradable than chemically-made ones. Research since about 2018 has shown dramatic results. In onions, seeds treated with silver or gold nanoparticles made from onion or turmeric byproducts germinated faster and produced more bulbs with higher yield. In wheat, priming seeds with neem-flower-derived AgNPs more than doubled germination rates in laboratory tests. Even in woody crops, eco-friendly nanopriming helps: biosynthesized AgNPs improved growth and drought tolerance in Acacia seedlings, boosting height by 60–150% and warding off soil fungus.

Workflow of Green Nanoparticle-Based Seed Priming:

- Plant extracts or agro-waste are used for the green synthesis of nanoparticles.
- The synthesized nanoparticles are applied to seeds through soaking or coating.
- Seed priming promotes faster and more uniform germination.
- It enhances seedling growth, vigor and stress tolerance.
- Improved plant establishment ultimately results in higher crop yield and better-quality produce.

- *Green Synthesis:* Plants contain compounds (like flavonoids or sugars) that can reduce metal salts to nanoparticles. For instance, turmeric or onion extracts make stable AgNPs, while tea extracts yield Cu NPs.
- *Nanopriming Treatment:* Seeds are soaked or coated with the NP suspension. Typical concentrations range from a few to ~50 mg of metal per litre.
- *Outcomes:* Treated seeds usually germinate quicker and more uniformly than untreated or water-primed seeds. They often have longer roots and shoots, higher chlorophyll, and better enzyme activity. Many studies report 20–100% improvements in germination percentage or seedling vigour.
- *Stress Resistance:* Crucially, nanopriming often makes plants more resilient. Under salt or drought stress, nano-primed seeds maintain high germination and growth 【. In one example, tomato seeds primed with 40 mg/L AgNPs (from a desert shrub extract) reached 90% germination under high salt, versus only 70% in controls. This stress tolerance is a key advantage in climate-challenged agriculture.

Methods Overview

Green synthesis of nanoparticles typically involves mixing a metal salt (e.g. $AgNO_3$ or $CuSO_4$) with a plant extract under mild heating. The plant compounds act as both reducing agents and capping/stabilizing agents. For example, one study used neem flower extract to make silver NPs about 35 nm in size. Another used green tea polyphenols and ascorbic acid with starch to make copper-based NPs (8 nm or 69 nm). The resulting NPs are filtered and usually characterized by UV-Vis, TEM or DLS to confirm size and shape.

Seeds are then primed by soaking in the NP solution. Protocols vary: soaking times of 2–24 hours are common, followed by drying and planting. Concentrations must be carefully chosen. Low-to-moderate doses often improve germination, whereas very high doses can be toxic. For instance, maize seeds primed with "ascorbic acid/starch" CuNPs (68 nm) accumulated phytotoxic Cu at ≥58 mg/L, hurting growth; but smaller "green tea" Cu NPs (8 nm) remained beneficial even at 116 mg/L.

Table 1: Summary table of representative studies, showing various green synthesis routes and their effects:

Plant source / Ag-roots	Nanoparticle	Seed species	Conc. (mg/L)	Observed effect
Onion byproduct (turmeric oil, onion peel)	AgNP, TNE†	Onion / watermelon	~20–60	+ germination, + emergence, + yield (up to +35%); no loss in quality.
Neem flower vs leaf extract	AgNP (35 nm)	Wheat	25–75	Higher germ% (up to +100% at 75 mg/L), longer roots/shoots, more antioxidants.
Green tea extract (*Camellia sinensis*)	Cu NP (8 nm)	Maize	14.5–116	Improved seedling biomass; smaller NPs (green tea) less toxic than larger starch-capped at high dose.
Green tea (Camellia sinensis) / Ascorbic acid	Cu NP (69 nm)	Maize	14.5–116	See above; ascorbic/starch-capped NPs began phytotoxic above ~58 mg/L.
Cotula cinerea (desert plant)	AgNP (15 nm)	Durum wheat	20–80	Under 150 mM NaCl, 40 mg/L gave 90% germ vs 70% control; roots ~86% longer; better yield traits in salt.

Syzygium cumini seed (not shown)	ZnO NP (18 nm)	Tomato	0.01–1 ppm	1 ppm ZnO-NP increased germination, vigor and antioxidant activity (as example; similar to Se NPs).
Selenium NPs (often biofabricated)	Se NP (size <100 nm)	Tomato	1–50 ppm	1 ppm gave +32% germination in trays; 10 ppm increased chlorophyll (+21%) and antioxidants (+39%).
Various plant extracts (ex: onion, capsicum)	AuNP, ZnO, CuO etc.	Multiple (tomato, cucumber, etc.)	20–100+	Consistent reports: nanopriming speeds up germination, increases enzyme activity and stress proteins.

TNE: turmeric oil nanoemulsion; AgNP: silver nanoparticle; ppm = mg/L (approx).

Most studies follow a similar steps: synthesize NPs, validate size/shape (e.g. UV-Vis, TEM), soak seeds, then measure germination rate, seedling length, chlorophyll, enzyme activity, etc.

Key Results and Mechanisms

Across many experiments, seed priming with green NPs consistently improves germination and early growth. In quantitative terms, improvements can range from tens to hundreds of percent. For example, seedling vigor index (a combined measure of germination percentage and seedling size) often doubles at optimal NP doses. In peas, iron-oxide NP-primed seeds showed higher drought resilience and yield. In chilli peppers, nano-priming boosted chlorophyll and antioxidant enzymes.

Mechanisms. Researchers propose several non-mutually exclusive ways that NPs aid germination:

- **Enhanced water uptake:** Nanoparticles can create nano-pores or alter seed-coat permeability, allowing quicker water inflow. Many primed seeds imbibe water faster, which speeds metabolic activation.
- **Activation of metabolism:** Once inside the seed, metal NPs slowly release ions (e.g. Ag^{+} or Cu^{2+}) that stimulate enzymes. Priming often raises α-amylase and protease activities, breaking down starch and proteins into simple nutrients for the embryo.
- **ROS signaling:** Nanoparticles induce a gentle reactive-oxygen species (ROS) burst. Far from damaging the seed, this mild oxidative signal can actually promote germination. It triggers stress-defense pathways and secondary metabolites. Studies note that optimized NP doses enhance antioxidant enzymes (superoxide dismutase, catalase, etc.) and reduce harmful oxidation (lipid peroxidation).
- **Gene regulation:** There is evidence NPs upregulate genes related to water transport (aquaporins) and stress tolerance. Proteomic analyses find that nano-priming seeds express more stress-protective proteins even at germination
- **Nutrient delivery:** Some NPs are basically nanofertilizers. For instance, ZnO or CuO NPs supply zinc or copper micronutrients directly to the germinating seedling, improving chlorophyll and photosynthesis in the young plant.

Practical Implications

For farmers and breeders, nanopriming offers several potential gains:

- **Uniform stands and faster crops:** Improved germination speed and uniformity means crops establish more evenly. This can translate to easier weed control and more efficient harvest scheduling. In high-value crops like watermelons or onions, a strong start is especially important. For example, AgNP-primed watermelons reached 31–35% higher yield in field trials, without any loss of fruit quality.

- **Stress resilience:** Treating seeds with biogenic NPs often protects them against drought, salinity, or pathogens right from the start. The Acacia study showed that AgNP-primed seedlings had much higher biomass and lower fungal infection under drought. In saline soils, wheat seeds primed with green AgNPs germinated and grew far better than untreated ones. This suggests nanopriming could be a tool in climate-smart agriculture.
- **Reduced inputs:** Because nano-primed plants grow more vigorously, farmers might need fewer re-sows, fertilizers or fungicides. In some cases, green NPs themselves have antimicrobial action (e.g. silver killing seed-borne fungi), reducing disease risk. Also, using plant wastes (onion skins, tea, etc.) to make NPs adds value to byproducts and cuts chemical usage.
- **Compatibility with organic or sustainable farming:** If the nanoparticles are truly benign (made without toxic chemicals), they could fit into eco-friendly farming systems. Many green NPs are seen as an "add-on" to conventional priming. For instance, popping seeds into water with a few ppm of silver or zinc NPs is low-tech and could be done on farms or by seed companies.

Limitations and Future Directions

Despite promising results, several cautions remain:

- **Toxicity at high dose:** Even "green" NPs can become toxic if overused. As noted, some Cu and ZnO NP studies found growth inhibition past optimal concentrations. Each nanoparticle and plant species requires trial-and-error to find safe levels.
- **Environmental fate:** Little is known about what happens to the nanoparticles after planting. Do they dissolve harmlessly, or accumulate in soil? Could they affect soil microbes or beneficial insects? Long-term ecotoxicology studies are needed before widescale adoption.
- **Standardization and scale-up:** Green synthesis methods vary from lab to lab. Scaling up consistent, high-quality NP production (especially as many rely on seasonal plant extracts) is a challenge. Regulatory frameworks for "nano-agrochemicals" are still nascent.
- **Mechanistic gaps:** Many positive outcomes have been measured, but the exact biological pathways need more study. For example, where exactly do nanoparticles localize in the seed? Advanced imaging and molecular studies (like the TEM work in the tomato-Se study are starting to answer these questions. Understanding how NPs interact with cell organelles and genes will help refine methods.
- **Crop specificity:** Effects can differ by crop. What works for wheat or tomato might not be the same for beans or flax. A broader database of "NP priming recipes" for different crops would help.
- **Synergy with other priming:** Future research could mix NPs with other treatments (e.g. hormones, beneficial microbes) to see if there are synergistic gains.

Looking ahead, we expect more field trials and multi-season studies. Early lab success must translate to real-world conditions. Combining nanopriming with smart fertilizer or precision irrigation could form integrated solutions. Advances in nanobiotechnology may yield new NPs (like biodegradable polymer NPs) for seed treatment. Ultimately, safe nano-priming could become a routine seed enhancement, akin to existing biopriming and coating technologies.

Conclusion

Green nanoparticle seed priming is a fresh frontier in crop science, marrying age-old botanical extracts with cutting-edge nanotech. It offers a simple way to rev up seeds: soak or coat them in a plant-made nanoparticle soup, and watch them germinate faster, grow stronger, and better resist stress. Multiple studies have shown big benefits in diverse crops and conditions. The underlying science – improved water uptake, metabolic activation, and mild signaling stress – makes sense of these results. For growers and researchers, the key is to harness the benefits while managing concentrations and understanding environmental impacts. With more research, standardized protocols, and regulatory clarity, green nanopriming could join the toolbox of sustainable agriculture. In summary, this technology shows how natural and nano can work together using plant wisdom to build tiny helpers that unlock seeds' full potential.

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