



Nanoparticles on Seed Germination

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Every crop begins with a seed that must absorb water, activate its enzymes, and push out a root. If this stage goes wrong, no later input can fully make up for it. Farmers have long soaked or coated seeds to improve emergence, and a newer approach adds nanoparticles to the process. Nanoparticles are particles roughly 1-100 nanometres across, and their tiny size gives them a very large surface area and unusual chemical behaviour. Agriculture needs better tools. It faces production losses from pests, climate change and depleting natural resources, while conventional practice relies on continuous use of pesticides and fertilisers that contaminate the environment. With food production needing to rise by an estimated 25-70% by 2050 to feed a population of 9-10 billion, even small gains at the seed stage matter. This article summarises what research shows about how nanoparticles affect germination, why the results differ so much, and what must be settled before farmers can use them with confidence.

Nano-Priming: Treating Seeds at the Nanoscale

Seed priming means hydrating seeds under controlled conditions so that germination-related processes begin before sowing. Nano-priming uses a nanoparticle suspension for this step, and it can alter seed metabolism and signaling pathways, affecting not only germination but the entire plant life cycle. Reviews list a range of potential benefits: improved germination and germination synchrony, protection of seeds during storage, greater resistance to abiotic and biotic stresses, and a reduced need for pesticides and fertilizers. Since many nanoparticles are antimicrobial, they can also help protect seeds, and nano-priming can be used to biofortify seeds with nutrients. A comparison of nanoparticle applications at different growth stages found that seed treatment most often improves germination, reduces contamination by plant pathogens, and increases stress tolerance. Nano-priming also appears economical in one respect: it uses only small concentrations.

How Nanoparticles Affect the Germinating Seed

- **Faster water uptake.** Imbibition is the first step of germination. Carbon nanotubes were shown to penetrate the thick seed coat of tomato and increase water uptake, and tomato seeds on nanotube medium germinated by day 3, while control seeds had not. The authors suggested that nanotubes may open new pores for water or regulate existing water channels (aquaporins), but they noted that the molecular mechanism is unclear.
- **Aquaporin gene activation.** Silver nanoparticles at 5 and 10 ppm were reported to raise the expression of aquaporin genes in rice, and in Arabidopsis, aquaporin transcript levels rose to about twice those of control plants.
- **Reactive oxygen species (ROS) signalling.** ROS are usually thought of as damaging, but at low levels they act as messengers that help start germination. Work on nano-priming proposed that nanoparticles generate beneficial ROS within an "oxidative window". In aged rice seeds, silver nano-priming produced more ROS than unprimed seeds, and the proposed mechanisms also included hydroxyl radicals that loosen cell walls and nanocatalysis of starch hydrolysis.

- **Hormone and gene effects.** In amaranth and cruciferous vegetables, photocatalytic titanium dioxide improved germination through gibberellins, the hormones that trigger reserve mobilisation. Reviews add that nano-priming can activate stress-related genes during germination.

Not every material helps water movement. Copper/copper oxide nanoparticles may block water channels and reduce water uptake, and an excess of metal nanoparticles can cause toxicity and abnormal cell division.

Evidence from Different Nanoparticles

Zinc oxide and nickel oxide

Zinc oxide has been studied heavily in cereals, partly because zinc is an essential micronutrient and zinc deficiency is a nutritional concern in countries like India. In wheat, ZnO nanoparticles of 40-50 nm increased shoot and root growth and chlorophyll compared with conventional zinc sources. Work in Iraq using leaf-extract-made ZnO nanoparticles of about 30 nm raised germination to 59.17% at 100 ppm from 24.17% in the control. Wheat primed with 5–500 ppm ZnO for four hours reached full germination at 250 ppm. A study on black gram found that NiO nano-priming at 50-100 ppm significantly improved germination and early seedling performance, and linked this to better water absorption and metabolic activation.

Iron oxide

Iron oxide priming has been tested mainly under water stress. In chickpea, germination stopped completely at the strongest simulated drought (−8 bar), yet priming still helped: iron nanoparticles of 40–60 nm at 8 g/L produced the highest vigour and were judged the most effective treatment, boosting germination percentage under drought and speed and vigour without it. Priming maize with iron oxide nanoparticles at 25-100 mg/L has likewise been reported to improve performance under limited water, and iron oxide priming of flax at 25-100 ppm improved growth and yield attributes. Green-synthesised Fe₃O₄ nanoparticles made from Ginkgo leaf extract have also been tested on drought-stressed alfalfa germination.

Titanium dioxide and silicon dioxide

Titanium dioxide shows why results are so hard to generalise. It has been reported as toxic because its photocatalytic action produces reactive oxygen species, and as beneficial to growth. A study on amaranth and cruciferous vegetables suggested the controversy comes down to dose: 0.1 and 0.2 mg/cm² improved germination and growth, while 1 mg/cm² damaged tissue. A review of TiO₂ concluded that effects range from negative to neutral to positive, and that positive effects on germination and vigour appear when the right concentration is chosen. Studies on pea and on marigold and lemon balm show that TiO₂ and SiO₂ can change germination, water supply, oxidative stress and biochemical traits, with responses that differ between species and materials.

Carbon nanotubes and silver

Carbon nanotubes are among the most striking cases: tomato seeds exposed to them germinated up to twice as fast as controls, with germination and biomass benefits reported in a concentration range of 0.1-200 µg/mL. Silver is more controversial. Reviews note that silver nanoparticles show size- and concentration-dependent toxicity and that adverse effects dominate in most studies, though neutral and beneficial effects also appear depending on species. In castor bean, silver nanoparticles had no significant effect on seedling growth even at 4,000 mg/L, while silver nitrate inhibited germination.

Why Results Differ: Dose, Size and Species

The same nanoparticle can help one crop and harm another, and can even reverse its effect at a higher dose. Reviews of seed nano-priming identify size, zeta potential (surface charge), and concentration as the properties that shape the biological response, and smaller particles cross biological barriers more efficiently. The optimum dose varies by crop. In a comparison of three crops, 500 ppm ZnO promoted radicle growth in wheat, 1,000 ppm in mung bean, and about 100 ppm in rice, and the study noted both positive and negative effects. Earlier testing of five

nanoparticle types on six plant species found that only zinc and zinc oxide significantly inhibited germination and root growth, even though low doses of ZnO helped in other work. The chemical form matters as well. Silver nanoparticles inhibited germination at low concentrations in one study yet never blocked it completely, and the authors concluded that germination tests alone are poorly suited to judging the environmental impact of silver. Nanoparticles made by green synthesis, using plant extracts as reducing agents, are increasingly used because conventional physical and chemical routes can involve toxic chemicals and high temperatures.

Challenges and Future Directions

Most of the evidence comes from Petri dishes and small pots. Real soils are more complex, and reviewers of TiO₂ have asked for longer experiments under environmentally relevant conditions, covering multigenerational effects and the best timing of application. Environmental safety is the other open question: researchers on silver nanoparticles call for deeper work to guide legislation and regulation. Practical adoption will need standard dose recommendations for each crop, field validation across seasons and soils, residue and safety data, and affordable production, for which green synthesis from agricultural by-products is a promising route.

Conclusion

Nanoparticles can speed germination, improve seedling vigour, and help seeds cope with stress such as drought, and the evidence spans wheat, black gram, chickpea, maize, tomato, and vegetables. The proposed explanations include easier water entry, active aquaporins, ROS and hormone signalling, and faster breakdown of stored starch. The same particles can inhibit germination when the dose is too high, or the material is unsuited to the crop. Nano-priming is therefore best seen as a promising, dose-sensitive technology whose safe use rests on field trials, careful dosing and regulation, not as a universal seed treatment.