

Innovative Seed Treatment Strategies for Enhanced Plant Health

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In contemporary Agriculture, seed treatment has undergone a remarkable transformation from a basic preventative measure to a cutting-edge technological intervention. Traditional practices focused mainly on applying fungicides or insecticides to seeds, but with rising concerns about environmental safety, pesticide resistance and climate stress, new approaches have been developed that combine protection, nutrition and sustainability. These advanced techniques not only safeguard seeds against pathogens and pests but also enhance germination, improve seedling vigour and support long-term crop resilience.

- Polymer and film coating technologies represent a key innovation in seed treatment. These coatings form a thin, consistent layer around the seed, effectively securing pesticides, nutrients, and biological agents. They help protect the seed from damage while enhancing the accuracy of ingredient delivery, ensuring the active substances are released in a way that supports optimal seed germination. A related technique is seed pelleting and encapsulation, where small or irregularly shaped seeds are coated with materials that standardize their size and shape. This process also incorporates fertilizers, microbes, or growth stimulants, enabling controlled release during the seed's early stages of growth.
- Nano-sized nutrients, such as zinc, iron, and copper, along with antimicrobial nanoparticles like silver, are applied in minimal quantities to offer efficient and eco-friendly solutions that promote seed germination and protect seedlings. Nanoformulations of active ingredients improve seed adhesion, enhance nutrient uptake and allow for very low doses with high effectiveness. Research has shown that properly designed nanoparticles can enhance germination, activate antioxidant defenses in seedlings, and promote early plant vigor. Biodegradable nanocarriers made from polysaccharides are being developed to reduce environmental persistence and risks. However, the effectiveness and safety of these nanoparticles depend on factors like particle size, dosage, coating composition, and plant species, with concerns about toxicity, safety and regulation remaining significant.

- Another significant advancement is the increased use of biological and microbial seed treatments. Beneficial microorganisms like *Trichoderma*, *Pseudomonas fluorescens*, and *Bacillus subtilis* are now commonly applied to seeds to control soil-borne diseases, fix nitrogen, and enhance root development. Improvements in formulation technologies have extended the viability of these microbes on seeds, overcoming previous limitations related to shelf life. At the same time, nanotechnology is being more frequently investigated as part of seed treatment strategies.
- Seed priming techniques also represent a modern shift in seed treatment. By partially hydrating seeds under controlled conditions, metabolic activities begin before sowing, resulting in faster and more uniform germination. Advanced forms of priming include osmopriming with osmotic agents, biopriming with beneficial microbes, and hormonal priming with growth regulators. These methods also increase seed tolerance to environmental stresses like drought, salinity and extreme temperatures. In addition, smart delivery systems are being designed to release nutrients or protective agents in response to soil conditions such as moisture levels or root exudates, making seed treatment more precise and efficient.
- Physical, non-chemical seed treatments, such as cold (non-thermal) plasma, targeted UV, magnetopriming, and hot-water treatments, offer pathogen reduction and seed surface modification without leaving behind persistent chemicals. Cold plasma, for instance, can modify the seed coat, enhancing water absorption, reducing microbial load on the surface, and triggering biochemical defenses. Several recent studies have shown significant improvements in germination rates and seedling growth after carefully controlled plasma exposure. These methods provide an alternative to chemical treatments, making them suitable for organic or low-input farming systems. However, they require precise control over dosage and treatment duration to prevent seed damage and the

development of scalable equipment for processing large seed batches.

- Innovative techniques such as RNA interference (RNAi) are paving the way for new advances in seed protection. RNAi-based treatments target and silence specific genes in pests or pathogens that threaten young seedlings, providing a precise, residue-free form of protection. In addition,

integrated formulations that combine both chemical and biological agents are becoming increasingly popular, as they deliver immediate and sustained benefits to crops. Digital and precision seed treatment machinery, equipped with sensors and artificial intelligence, further improve accuracy by ensuring uniform coatings, minimizing waste, and enabling traceability and quality control.

Table 1: Seed Treatment Approaches

Seed Treatment Method	Description	Benefits	Examples
Chemical Treatment	Seed Application of fungicides, insecticides, and nematicides.	Protects seeds from pests, diseases, and pathogens.	Captan, Imidacloprid, Metalaxyl, Thiram
Biological Treatment	Seed Introduction of beneficial microbes like bacteria or fungi.	Enhances plant growth, reduces disease susceptibility.	<i>Trichoderma</i> spp., <i>Bacillus</i> spp.
Hot Water Treatment	Soaking seeds in hot water to kill pathogens.	Disinfects seeds without affecting their viability.	-
UV Radiation Treatment	Exposure to UV light to disinfect seeds.	Kills surface pathogens, sterilizes seeds.	-
Coating with Nutrients/Biostimulants	Coating seeds with essential nutrients or growth stimulants.	Improves germination and early plant growth.	Zinc, Copper, Humic Acids, Seaweed Extracts
Polymers and Gums Coating	Coating seeds with biopolymers or gums for protection.	Protects from physical damage, ensures uniform depth.	Polymer-based coatings, Fertilizer coatings
Nano-coatings	Applying nanoparticles to create protective seed layers.	Controlled release of pesticides/fertilizers.	Nano-silver, Nano-carbon, Nano-silica
Priming	Pre-soaking seeds to initiate early growth.	Promotes faster, uniform germination.	Hydro-priming, Osmotic priming

In conclusion, these advanced seed treatment technologies mark a transformative shift in crop production. They do more than just protect seeds; they enhance crop establishment, decrease reliance on field pesticide

applications, and support sustainable farming practices. By integrating science, technology, and ecological principles, modern seed treatments not only boost yields and improve crop performance but also play a key role in tackling the challenges of food security and environmental conservation in the context of climate change.
