

Seed Priming Technologies Using Biostimulants and Nanomaterials: Enhancing Germination, Vigour and Stress Resilience in Modern Agriculture

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Abstract

Seed priming is an advanced pre-sowing technique that enhances germination rate, seedling vigour, and crop establishment by initiating early metabolic processes without allowing radicle emergence. In recent years, the use of biostimulants and nanomaterials in seed priming has gained significant attention for improving plant growth, nutrient use efficiency, and tolerance to environmental stresses. Biostimulants such as seaweed extracts, humic substances, amino acids, beneficial microbes, and plant growth regulators stimulate physiological processes that improve seed performance. Nanomaterials such as nano-silica, nano-zinc, nano-iron, and nano-chitosan improve nutrient availability and seed metabolism through enhanced absorption and controlled release mechanisms. Integration of biostimulants and nanotechnology in seed priming represents an innovative and eco-friendly strategy for improving crop productivity and sustainability in modern agriculture.

Introduction

Successful crop production begins with good quality seeds and proper crop establishment. Germination is a critical stage in the plant life cycle, as it determines plant population, uniform growth, and yield potential. However, many seeds face challenges such as poor germination, low vigour, delayed emergence, and susceptibility to environmental stresses such as drought, salinity, temperature extremes, and soil nutrient deficiency.

Seed priming is a physiological technique in which seeds are partially hydrated under controlled conditions to activate early metabolic activities required for germination. After hydration, seeds are dried back to their original moisture content so that they can be stored or sown later. Primed seeds show faster and more uniform germination compared to untreated seeds because biochemical processes such as enzyme activation, protein synthesis, DNA repair, and membrane stabilization are initiated during priming.

Traditional seed priming methods include hydropriming, osmopriming, halopriming, and hormonal priming. While these methods improve germination, modern research has introduced new approaches using biostimulants and nanomaterials to further enhance seed performance. These innovative approaches improve nutrient uptake, activate plant defence mechanisms, and enhance

tolerance to abiotic stresses such as drought, salinity, and temperature fluctuations.

Biostimulants and nanomaterials provide an environmentally friendly alternative to excessive chemical inputs. They support sustainable agriculture by improving seed efficiency and reducing dependence on synthetic fertilizers and pesticides. As agriculture faces challenges related to climate change, soil degradation, and resource limitations, seed priming technologies offer a simple and cost-effective solution to improve crop establishment and productivity.

Concept of Seed Priming

Seed priming is a controlled hydration process that allows seeds to absorb water up to a level that activates metabolic processes necessary for germination but prevents radicle emergence. During priming, several biochemical and physiological changes occur within the seed.

Cell membranes repair damage that may have occurred during storage. Enzymes responsible for mobilizing stored food reserves become active. Energy metabolism increases, enabling the seed to prepare for rapid growth once it is sown in soil. Primed seeds show improved enzyme activity such as amylase, protease, and lipase, which help convert stored carbohydrates, proteins, and lipids into energy required for seedling growth.

Seed priming also enhances antioxidant activity within the seed, protecting cells from oxidative damage. As a result, primed seeds perform better under stress conditions and show improved germination even in suboptimal environmental conditions.

Role of Biostimulants in Seed Priming

Biostimulants are natural or biologically derived substances that stimulate plant growth and development by enhancing physiological processes. They do not act as conventional fertilizers but improve plant performance through improved nutrient efficiency, hormone balance, and stress tolerance. Seaweed extracts are widely used biostimulants that contain natural plant growth regulators such as auxins, cytokinins, and gibberellins. These compounds promote cell division, root development, and seedling growth. Humic and fulvic acids improve nutrient availability and enhance root growth. Amino acids act as building blocks for proteins and enzymes required for metabolic processes.

Beneficial microorganisms such as plant growth promoting rhizobacteria improve seed germination and protect seedlings from soil-borne pathogens. These microbes produce phytohormones, solubilize nutrients, and enhance stress tolerance. Chitosan, a natural biopolymer derived from chitin, stimulates plant defence responses and improves resistance against diseases. Biostimulant-based priming enhances enzyme activity, improves membrane integrity, and activates biochemical pathways that support early seedling growth. This results in uniform crop establishment and improved productivity.

Role of Nanomaterials in Seed Priming

Nanotechnology has opened new possibilities for improving seed priming efficiency. Nanomaterials possess very small particle size and large surface area, which enhances their reactivity and absorption by seeds. Nano-sized nutrients provide improved bioavailability compared to conventional fertilizers. Nano-zinc, nano-iron, nano-silica, and nano-titanium dioxide are commonly studied nanomaterials used in seed priming. These nanoparticles enhance seed metabolism by improving enzyme activity and nutrient mobilization. Nano-silica improves seed resistance to abiotic stresses such as drought and salinity by strengthening cell walls and improving water retention.

Nano-chitosan acts as both a biostimulant and nano-carrier, improving nutrient delivery and activating plant defence mechanisms. Nanoparticles penetrate seed coats easily and release nutrients slowly, ensuring continuous supply during early seedling growth. Nanomaterials also improve antioxidant enzyme activity, reducing oxidative stress during germination. Improved nutrient availability leads to better root growth, shoot development, and biomass accumulation.

Mechanism of Seed Priming Using Biostimulants and Nanomaterials

Seed priming using biostimulants and nanomaterials activates several physiological processes. Hydration triggers metabolic repair processes such as restoration of membrane structure and DNA repair. Biostimulants stimulate enzyme production and hormone balance, promoting early germination. Nanoparticles improve permeability of seed coat and enhance nutrient uptake efficiency. They act as carriers that deliver nutrients directly to the embryo. Enhanced enzyme activity promotes faster breakdown of stored food materials, providing energy for rapid seedling growth.

Primed seeds exhibit improved stress tolerance because antioxidant enzymes reduce harmful effects of reactive oxygen species. Improved root development

increases nutrient and water uptake efficiency, helping plants survive under drought or nutrient deficiency conditions.

Table 1. Seed Priming Technologies Using Biostimulants and Nanomaterials

Priming Agent	Type	Mode of Action	Benefits to Crop
Seaweed extract	Biostimulant	Provides natural plant growth hormones	Faster germination and improved root growth
Humic acid	Biostimulant	Enhances nutrient availability and enzyme activity	Improved seedling vigour
Amino acids	Biostimulant	Supports protein synthesis and metabolism	Enhanced growth and stress tolerance
PGPR microbes	Biostimulant	Produces phytohormones and solubilizes nutrients	Improved plant health
Chitosan	Biostimulant	Activates plant defence mechanisms	Increased disease resistance
Nano zinc oxide	Nanomaterial	Improves enzyme activity and nutrient metabolism	Enhanced seed germination
Nano silica	Nanomaterial	Improves stress tolerance and cell wall strength	Increased drought tolerance
Nano iron	Nanomaterial	Enhances chlorophyll synthesis	Improved plant growth
Nano chitosan	Nano-biostimulant	Controlled nutrient release and defence activation	Improved seedling vigour

Advantages of Biostimulant and Nano-Priming

Seed priming using biostimulants and nanomaterials offers several advantages compared to conventional priming methods. It improves germination rate, reduces time required for emergence, and ensures uniform crop stand. Enhanced enzyme activity improves mobilization of stored nutrients, leading to faster seedling growth. These technologies improve plant tolerance to abiotic stresses such as drought, salinity, temperature stress, and nutrient deficiency. Improved root development enhances nutrient absorption efficiency. Reduced seedling mortality leads to better crop establishment. Biostimulants and nanomaterials also reduce dependency on excessive chemical fertilizers and pesticides. Improved nutrient use efficiency reduces

environmental pollution. These technologies support sustainable agriculture by promoting eco-friendly crop production practices.

Future Scope of Seed Priming Technologies

Future research is focusing on developing smart nano-carriers that release nutrients in response to environmental conditions. Integration of nanotechnology with biological inputs may further enhance efficiency of seed treatments. Development of low-cost priming technologies suitable for small farmers will increase adoption. Combination of seed priming with precision agriculture practices may further improve crop productivity. Seed companies are increasingly exploring advanced priming formulations that improve seed performance under climate

stress conditions. Such innovations will play an important role in climate-resilient agriculture.

Conclusion

Seed priming technologies using biostimulants and nanomaterials represent an innovative and sustainable approach to improve germination, seedling vigour, and crop productivity. Biostimulants enhance physiological processes and improve stress tolerance, while nanomaterials improve nutrient delivery and metabolic efficiency. Integration of biological and nano-based inputs in seed priming reduces dependence on chemical inputs and supports environmentally friendly agriculture. As research advances, these technologies are expected to play a major role in improving crop establishment and ensuring food security under changing climatic conditions.
