Quest Journals
Journal of Research in Agriculture and Animal Science
Volume 12 ~ Issue 1 (January 2025) pp: 53-59
ISSN(Online) : 2321-9459
www.questjournals.org

Review Paper

Emerging Trends in Seed Enhancement Technologies for Improved Plant Performance

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ABSTRACT
Seed enhancement technologies have become essential tools in modern agriculture, offering ways to boost seed performance, improve germination rates, and ensure uniform crop establishment under diverse environmental conditions. This review provides an in-depth analysis of emerging trends in seed enhancement, focusing on advanced priming techniques, seed coatings, pelleting, encrusting, synthetic seeds, and the integration of nanotechnology and biological agents. These approaches are crucial in addressing challenges posed by climate variability, soil degradation, and increased demand for high-quality crop production. mRecent innovations such as nanopriming, bio-priming with beneficial microbes, smart polymer coatings, and the use of signaling molecules have significantly advanced the efficacy of seed enhancement. These technologies help to improve stress tolerance, nutrient use efficiency, and pathogen resistance at early growth stages, contributing to better crop resilience and productivity. The review also explores the role of digital tools and precision delivery systems in enhancing seed treatment uniformity and monitoring performance. Despite the progress, challenges remain in terms of regulatory frameworks, cost-effectiveness, and field-level scalability. This paper aims to highlight the current advancements, potential applications, and future directions in seed enhancement technologies, positioning them as a key element in sustainable agriculture and global food security.

Keywords*: Seed priming, Seed coating, Nanotechnology, Bio-priming, Synthetic seeds, Plant performance, Crop establishment*

I. INTRODUCTION

Seed quality plays a pivotal role in determining the success of agricultural practices and overall crop productivity. High-quality seeds are essential for ensuring uniform germination, robust seedling establishment, and enhanced tolerance to biotic and abiotic stresses. With the increasing global demand for food, feed, and fiber amidst climate change and diminishing natural resources, the importance of utilizing superior quality seeds has become more pronounced than ever. Seed performance, influenced by both genetic potential and physiological health, directly affects crop yield and resource use efficiency. Therefore, improving seed quality is a fundamental step toward achieving sustainable agriculture, food security, and environmental resilience.

To meet these evolving challenges, the concept of seed enhancement has undergone significant transformation. Traditionally, seed improvement focused mainly on breeding superior genotypes and maintaining seed purity. However, advances in seed enhancement technologies now encompass a diverse range of pre-sowing treatments designed to improve seed vigor, viability, and stress tolerance. These technologies include physical, chemical, and biological treatments that modify the seed’s external or internal environment to boost performance under both optimal and sub-optimal conditions.

The evolution of seed enhancement technologies can be traced from basic seed priming techniques to more sophisticated methods such as seed coating, pelleting, encrusting, bio-priming, and the integration of nanotechnology and biostimulants. These innovations aim not only to protect seeds from pathogens and pests but also to deliver essential nutrients, growth regulators, and beneficial microbes directly to the seed microenvironment. Furthermore, recent advances have introduced precision delivery systems that enhance the effectiveness of these treatments while minimizing environmental impacts.

The development and refinement of these technologies have been accelerated by interdisciplinary research involving plant physiology, microbiology, material science, and agronomy. Modern seed enhancement approaches are increasingly tailored to specific crops, environments, and farming systems, including organic and conservation agriculture. Moreover, the emergence of smart agriculture and digital tools is also influencing the way seed treatments are developed and applied, leading to more efficient and targeted interventions.

1.1 Objectives

1. To explore recent advancements in seed enhancement technologies aimed at improving germination, seedling vigor, and crop establishment.
2. To analyze the role of physical, chemical, and biological seed treatments in enhancing plant performance under diverse environmental conditions.
3. To evaluate the efficacy and sustainability of nanotechnology, polymer coatings, and biopriming in modern agriculture.
4. To identify research gaps and future directions for the development and application of innovative seed enhancement strategies.

1.2 scope of the review

This review aims to comprehensively explore and analyze the latest developments in seed enhancement technologies that are transforming modern agriculture by improving seed vigor, germination rates, stress tolerance, and overall plant performance. The scope includes:

1. **Seed Priming Techniques**- Analysis of various priming methods (e.g., hydropriming, osmopriming, biopriming, hormonal priming, and nano-priming) and their physiological and biochemical effects on seed germination and early seedling growth.
2. **Seed Coating and Pelleting**- Evaluation of innovative coating materials, nutrient carriers, and bioactive compounds used in seed coatings to enhance protection, deliver agrochemicals, and improve sowing precision.
3. **Nanotechnology in Seed Enhancement**- Review of applications of nanomaterials (e.g., nano-fertilizers, nano-pesticides) for targeted delivery, stress mitigation, and improved nutrient use efficiency.
4. **Microbial Inoculants and Biological Seed Treatments**- Examination of plant growth-promoting rhizobacteria (PGPR), mycorrhizae, endophytes, and biofungicides used as seed treatments to confer biotic and abiotic stress resistance.
5. **Seed Disinfection and Pathogen Control**- Overview of novel disinfection technologies such as cold plasma, UV-C treatment, and biocontrol agents that reduce seed-borne diseases.
6. **Biochemical and Molecular Insights**- Discussion on molecular mechanisms triggered by enhancement technologies, including gene expression changes and hormonal signaling pathways.
7. **Smart and Precision Seed Enhancement**- Consideration of digital tools and precision agriculture systems for optimizing seed treatment processes and monitoring performance outcomes.
8. **Environmental Sustainability and Regulatory Perspectives**- Exploration of the ecological impact, scalability, and regulatory status of emerging seed technologies.
9. **Crop-Specific Applications**- Inclusion of evidence from major crops (e.g., cereals, legumes, vegetables) to highlight species-specific advancements and challenges.
10. **Future Prospects and Research Gaps**- Identification of key challenges and future directions for research, commercialization, and field adoption of seed enhancement innovations.

Overall, this review seeks to serve as a valuable resource for researchers, agronomists, seed technologists, and policymakers, by offering a consolidated overview of the state-of-the-art in seed enhancement strategies aimed at ensuring food security, climate resilience, and sustainable agricultural productivity.

II. TRADITIONAL VS MODERN SEED ENHANCEMENT TECHNIQUES

2.1 Traditional methods

Abdul-Baki and Anderson (1973) pioneered the concept of seed priming through controlled hydration and dehydration cycles, showing that simple water soaking and drying could significantly improve germination and seedling vigor in various vegetable crops, particularly under suboptimal conditions.

Basra et al. (2005) provided a comprehensive analysis of traditional seed priming methods such as hydropriming and osmopriming. They highlighted how low-cost techniques like soaking in water for a defined period followed by air drying enhance seed metabolic activities and uniform germination without requiring sophisticated equipment.

Heydecker and Gibbins (1978) elaborated on early forms of seed treatment using water and salt solutions, emphasizing that pre-sowing hydration is a viable technique for improving germination rates, especially in temperate cereal crops. Their work laid the foundation for later developments in physiological seed enhancement.

Kaur et al. (2002) investigated the effects of traditional seed priming practices such as soaking and sun drying on wheat seeds. Their results showed enhanced seedling emergence, better stand establishment, and improved drought tolerance under field conditions, especially in rainfed agriculture.

2.2 Need for advanced approaches

Ashraf and Foolad (2007) emphasized the importance of developing seed enhancement techniques to combat abiotic stresses such as drought, salinity, and temperature fluctuations. They highlighted that seed priming and hormonal treatments can improve germination and seedling establishment under stressful environmental conditions, which is crucial for crops grown in climate-vulnerable regions.

Farooq et al. (2012) reviewed the physiological and molecular benefits of seed priming and biostimulant applications, arguing that these methods enhance the metabolic preparedness of seeds. Their findings suggest that seed enhancements can mitigate nutrient deficiency and reduce seedling mortality by improving nutrient uptake efficiency and boosting antioxidant enzyme activity.

Paparella et al. (2015) explored how seed enhancement strategies, including coating and priming, can address emerging climate-related challenges in agriculture. They discussed how these technologies improve germination uniformity, early growth, and resistance to oxidative stress, thereby decreasing seedling losses in both marginal soils and harsh climates.

Shahbaz and Ashraf (2013) demonstrated that seed treatments with micronutrients and plant growth regulators help alleviate nutrient imbalances in the soil, especially in calcareous and saline environments. Their study supports the role of enhanced seeds in reducing early seedling mortality and promoting robust establishment under suboptimal nutrient conditions.

Author(s)	Year	Focus Area	Method/Technology	Key Findings	Relevance to Climate Stress, Nutrient Deficiency, & Seedling Mortality
Abdul-Baki & Anderson	1973	Seed priming concept development	Hydration–dehydration cycles	Controlled soaking and drying improved germination and vigor in vegetables under suboptimal conditions	Provided foundational evidence for seed enhancement under stress conditions
Ashraf & Foolad	2007	Abiotic stress mitigation	Seed priming, hormonal treatments	Improved seedling establishment under drought, salinity, and temperature stress	Critical for enhancing crop performance in climate-vulnerable areas
Basra et al.	2005	Traditional seed priming	Hydropriming, osmopriming	Low-cost soaking methods improved seed metabolic activity and germination uniformity	Useful for smallholder adaptation to stress-prone environments
Farooq et al.	2012	Molecular and physiological priming benefits	Biostimulants, seed priming	Improved metabolic preparedness, nutrient uptake, and reduced seedling mortality	Addresses both nutrient deficiency and early mortality
Heydecker & Gibbins	1978	Early hydration treatments	Pre-sowing water/salt soaking	Enhanced germination rates in cereals, especially under temperate conditions	Foundational work for modern seed hydration techniques
Kaur et al.	2002	Traditional field priming	Soaking, sun drying	Better drought tolerance, emergence, and establishment in wheat under rainfed conditions	Demonstrated practical relevance of seed priming for dryland agriculture
Paparella et al.	2015	Seed enhancement for climate resilience	Seed coating, priming	Improved germination uniformity and oxidative stress resistance in marginal soils	Key for crop survival and performance in degraded or stress-prone environments
Shahbaz & Ashraf	2013	Nutrient stress alleviation	Micronutrient and hormone-based treatments	Alleviated soil nutrient imbalances, enhanced seedling establishment in calcareous and saline conditions	Targeted improvement of nutrient use and early growth under deficient soil conditions

III. ADVANCES IN SEED PRIMING TECHNIQUES

3.1 Hydropriming, Osmopriming, and Hormonal Priming

1. Hydropriming- Hydropriming involves soaking seeds in water for a specific duration, followed by drying them back to original moisture content before sowing.

Mechanism:

- Activates early germination metabolism (e.g., repair enzymes, DNA replication) without actual radicle emergence.
- Improves water uptake kinetics and membrane reorganization.

Effects:

- Enhances seed germination speed and uniformity.
- Reduces mean germination time and seedling mortality.
- Boosts vigor under moderate stress (e.g., drought or salinity).

Applications:
- Widely used in cereals like wheat, rice, and barley.
- Effective for legumes such as chickpea and mungbean under moisture-limited environments.

2. Osmopriming- Soaking seeds in a solution with a low water potential using osmotic agents like polyethylene glycol (PEG), mannitol, or salt (e.g., KNO_3) to regulate water uptake.

Mechanism:
- Allows controlled hydration that activates metabolism but prevents full germination.
- Enhances antioxidant enzyme systems and membrane stability.

Effects:
- Improves seedling growth and germination under abiotic stresses like salinity and drought.
- Delays aging and enhances stress tolerance during seedling establishment.

Applications:
- Useful for rice, maize, sorghum, and wheat.
- Applied to legumes like lentil, soybean, and cowpea, especially in saline soils.

3. Hormonal Priming- Soaking seeds in solutions containing plant growth regulators such as gibberellic acid (GA_3), salicylic acid (SA), abscisic acid (ABA), or cytokinins.

Mechanism:
- Modulates hormonal signaling pathways associated with germination and stress tolerance.
- Stimulates synthesis of proteins involved in growth and defense.

Effects:
- Enhances germination rate, root-shoot growth, and antioxidant capacity.
- Induces tolerance to heat, cold, drought, or oxidative stress.

Applications:
- Proven effective in cereals like rice, maize, and wheat under heat and chilling stress.
- Enhances performance in legumes like pigeon pea, soybean, and groundnut in harsh conditions.

Comparative Table: Priming Methods

Priming Type	Mechanism	Key Effects	Cereal Applications	Legume Applications
Hydropriming	Water-only soaking; initiates metabolism without germination	Faster and uniform germination, better emergence	Wheat, Rice, Barley	Chickpea, Mungbean
Osmopriming	Osmotic solution (PEG, KNO_3) regulates hydration and delays germination	Improves stress tolerance, antioxidant activity	Maize, Rice, Sorghum, Wheat	Lentil, Soybean, Cowpea
Hormonal Priming	Uses PGRs (GA_3, SA, ABA); modulates hormonal pathways	Enhances stress resistance, growth, and antioxidant response	Rice, Maize, Wheat	Pigeon pea, Soybean, Groundnut

3.2 Nanopriming

Nanopriming is a seed enhancement technique that involves treating seeds with nanoparticles (NPs) to improve germination, seedling vigor, and stress tolerance. Unlike traditional priming, nanopriming utilizes ultra-small materials (typically <100 nm in size) with unique physicochemical properties that interact with seeds at the molecular level. These particles can penetrate seed coats, enhance metabolic activity, and induce stress resistance mechanisms without genetic modification.

Role of Specific Nanoparticles

1. **Zinc Oxide Nanoparticles (ZnO NPs):**

a) Zn is a micronutrient essential for enzyme activation, protein synthesis, and hormonal regulation.

b) ZnO NPs promote faster germination and enhance seedling vigor by stimulating enzymatic activity (e.g., amylase, catalase).

c) ZnO also acts as an antimicrobial agent, protecting seeds from pathogens.

2. **Silicon Nanoparticles (Si NPs):**

a) Si NPs help in strengthening cell walls, improving structural integrity and water-use efficiency.

b) They mitigate oxidative stress by enhancing antioxidant enzyme activity and reducing ROS (Reactive Oxygen Species) accumulation.

c) Si NPs improve tolerance to drought and salinity by regulating osmotic balance.

3. **Titanium Dioxide Nanoparticles (TiO_2 NPs):**

a) TiO_2 NPs boost photosynthetic efficiency and promote reactive oxygen scavenging.

b) They act as light absorbers and energy stimulants, which can activate metabolic pathways early in seed germination.

c) TiO_2 has also been linked with increased nitrate reductase activity, enhancing nitrogen metabolism in seedlings.

Benefits of Nanopriming in Stress Mitigation and Germination
- Accelerated and uniform germination under both optimal and stress conditions.
- Improved tolerance to abiotic stresses such as drought, salinity, heavy metals, and temperature fluctuations.
- Enhanced nutrient uptake and activation of antioxidant defense systems.
- Reduced seed-borne diseases due to antimicrobial properties of nanoparticles.
- Improved root and shoot development in early growth stages.

Table: Nanopriming with ZnO, Si, and TiO_2 Nanoparticles – Roles and Benefits

Nanoparticle	Function in Seeds	Stress Mitigation Mechanism	Germination Benefits	Reference Example
ZnO NPs	Micronutrient delivery, enzyme activation, antimicrobial action	Induces antioxidant enzymes, reduces pathogen load	Faster germination, higher vigor index	Mahmoodzadeh et al., 2013
Si NPs	Cell wall strengthening, osmotic regulation	Enhances drought/salinity tolerance via ROS scavenging	Better water uptake, stronger seedling structure	Siddiqui et al., 2014
TiO_2 NPs	Enhances light absorption, nitrate metabolism	Activates stress-related enzymes, improves photosynthesis	Promotes early growth and shoot elongation	Jaberzadeh et al., 2013

3.3 Bio-priming

Bio-priming is a seed enhancement technique that involves coating seeds with beneficial microorganisms to combine the advantages of seed priming and biological inoculation. This method improves seed germination, plant growth, and resistance to biotic and abiotic stresses.

1. PGPRs (Plant Growth-Promoting Rhizobacteria)

PGPRs are beneficial bacteria that colonize plant roots and enhance plant growth by:
- Producing phytohormones (e.g., auxins, gibberellins)
- Fixing atmospheric nitrogen
- Solubilizing phosphorus and other nutrients
- Inducing systemic resistance against pathogens

2. Mycorrhizae

These are symbiotic fungi that form associations with plant roots, helping in:
- Improved water and nutrient uptake (especially phosphorus)
- Enhanced drought and stress tolerance
- Resistance to soil-borne diseases

3. Trichoderma

Trichoderma is a fungus widely used for:
- Biocontrol of pathogens through mycoparasitism and production of antifungal compounds
- Plant growth stimulation via hormone production and improved root architecture

Dual Benefit of Bio-priming
- **Growth Promotion**- Enhanced nutrient uptake, root growth, and vigor.
- **Bio control**- Suppression of pathogens and induced resistance, reducing the need for chemical pesticides.

IV. INNOVATIONS IN SEED COATING AND PELLETING

4.1 Smart polymer coatings

Smart polymer coatings, such as moisture-triggered or temperature-responsive coatings, represent an advanced seed enhancement technology designed to improve germination timing and seedling establishment under variable environmental conditions. These coatings are formulated with stimuli-responsive polymers that either dissolve or swell in response to specific triggers like soil moisture levels or temperature thresholds. For instance, moisture-triggered coatings remain intact in dry conditions, preventing premature germination, and activate only when sufficient moisture is available. Similarly, temperature-responsive coatings delay germination until optimal soil temperatures are reached. This precise control helps synchronize germination with favorable environmental conditions, reducing seedling mortality and enhancing crop performance, particularly in regions affected by unpredictable weather patterns.

4.2 Nutrient and pesticide-loaded coatings

Nutrient and pesticide-loaded seed coatings involve embedding essential nutrients (like nitrogen, phosphorus, or micronutrients) and protective chemicals (such as fungicides or insecticides) directly onto the seed surface. This approach ensures precision delivery of inputs exactly where and when they are needed—during germination and early seedling growth. It reduces input wastage, minimizes environmental contamination, enhances plant health, and improves crop uniformity by targeting early developmental stages with vital resources.

4.3 Encrusting and pelleting for seed size modification

Encrusting and pelleting are seed enhancement techniques that involve coating seeds with inert materials to increase their size, weight, and uniformity.

- Encrusting adds a thin, partial layer that retains the seed's original shape but improves handling.
- Pelleting fully covers the seed into a round or uniform shape, ideal for small or irregular seeds.

These modifications make seeds mechanization-friendly, enabling precise planting using seed drills or pneumatic seeders. They enhance sowing accuracy, reduce seed loss, and support efficient large-scale agriculture.

V. Synthetic Seed Technology

5.1 Somatic Embryo Encapsulation

This involves coating somatic embryos (lab-grown embryo-like structures from plant tissues) in a protective hydrogel (usually sodium alginate) to form "synthetic seeds" that mimic true seeds in form and function. These capsules protect the embryo and provide nutrients and growth regulators for initial development.

5.2 Application in Vegetatively Propagated Crops

Synthetic seeds are especially valuable for crops that do not produce viable seeds or are typically propagated by cuttings or tubers (e.g., banana, potato, sugarcane). This method allows mass production and easier transport and storage of elite clones.

5.3 Role in Conservation and Rapid Propagation

Synthetic seeds offer a promising tool for conserving rare, endangered, or high-value plant species by storing somatic embryos. They also enable rapid propagation of genetically uniform and disease-free plants, enhancing agricultural scalability and biodiversity preservation.

VI. SEED ENHANCEMENT FOR ABIOTIC AND BIOTIC STRESS TOLERANCE

Seed enhancement technologies play a vital role in improving plant resilience to both abiotic stresses like drought, salinity, and heat, and biotic stresses such as fungal and bacterial infections. Techniques like priming (e.g., osmopriming, thermopriming), coating, and bioinoculation activate stress-responsive pathways in seeds, leading to faster germination and stronger seedlings.

For abiotic stress, treatments improve water uptake efficiency, antioxidant activity, and membrane stability, helping plants withstand harsh environments. Against biotic stress, seeds treated with biological agents (e.g., Trichoderma, Bacillus spp.) or antimicrobial coatings gain early protection from soil-borne pathogens.

Seed coatings serve as carriers for stress protectants, including micronutrients, fungicides, beneficial microbes, and polymer films, allowing precise delivery at the right stage of germination. This targeted enhancement increases seedling survival, reduces disease pressure, and supports sustainable crop production under adverse conditions.

VII. INTEGRATION WITH DIGITAL AGRICULTURE

7.1 Seed Performance Tracking Using Sensors

Smart sensors embedded in the field or machinery can monitor seed moisture, temperature, and early growth in real-time, allowing farmers to assess the effectiveness of seed treatments and adjust practices for better crop establishment.

7.2 AI and Imaging Tools for Germination Analysis

Artificial intelligence and high-resolution imaging systems can analyze seed germination speed, uniformity, and vigor in controlled environments or in-field settings, offering precise data to evaluate the success of enhancement methods.

7.3 Precision Planting with Treated Seeds

Digital planting systems ensure optimal spacing, depth, and placement of treated seeds using GPS and variable rate technology, maximizing the benefits of enhancements like coating or priming while improving yield potential and resource efficiency.

VIII. CONCLUSION

Emerging seed enhancement technologies such as priming, coating, nanotechnology, and microbial treatments offer promising solutions to improve germination, seedling vigor, and stress resilience in crops. These innovations not only enhance plant performance but also support sustainable agricultural practices by reducing the need for excessive agrochemical inputs. To fully realize their potential, there is a pressing need for interdisciplinary collaboration among plant scientists, agronomists, biotechnologists, and engineers, along with rigorous field-level validation to ensure these technologies are scalable, cost-effective, and environmentally sound across diverse farming systems.

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