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Seed Coating Technologies for Climate-Resilient Agriculture

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Abstract

Unstable climatic conditions have increasingly affected crop establishment, particularly during seed germination and early seedling growth. Environmental stresses such as water scarcity, soil salinity, elevated temperature, and irregular rainfall often lead to poor emergence and weak crop stands. Seed coating technology provides a focused strategy to improve seed performance under such stress conditions. By applying functional materials directly onto the seed surface, coating techniques support moisture retention, nutrient availability, biological protection, and early seedling vigor. As a result, seed coating has gained importance as a practical component of climate-resilient and sustainable agriculture (Pedrini *et al.,* 2017).

Keywords: coating, pelleting , climate resilient, absorbent, bio stimulant

1. Introduction

Climate change has become a serious concern for agricultural sustainability, with its effects being most evident during the early stages of crop growth. Seed germination is widely considered the most sensitive phase of the plant life cycle, as it determines plant population and uniformity in the field (Finch-Savage & Bassel, 2016). Failure at this stage often results in uneven crop establishment and yield instability, particularly in rainfed and stress-prone regions.

Seed coating is a seed enhancement approach aimed at improving seed performance under unfavorable environmental conditions. In this technique, seeds are covered with carefully selected materials that assist hydration, supply nutrients, protect against pathogens, or stimulate physiological activity. Since these inputs are placed directly on the seed, their efficiency is improved while overall input use is reduced, making seed coating suitable for climate-smart agricultural systems (Taylor *et al*., 2001).

2. Major Seed Coating Technologies

2.1 Film Coating

Film coating involves covering seeds with a thin protective layer that does not significantly alter seed size or shape. This method improves seed flow during sowing and minimizes dust formation. In addition, film coatings regulate water uptake, allowing seeds to absorb moisture gradually and reducing stress caused by sudden hydration under adverse environmental conditions (Halmer, 2008).

2.2 Pelleting and Encrusting

Pelleting and encrusting are commonly applied to small or irregularly shaped seeds. Pelleting produces uniform, round seeds that improve sowing precision, whereas encrusting partially covers the seed while retaining its original shape. These techniques also allow the inclusion of nutrients, pesticides, or biological agents that support early seedling growth under stressful soil environments (Pedrini *et al*., 2017).

2.3 Superabsorbent Polymer Coatings

Superabsorbent polymers have the ability to absorb and retain large quantities of water. When used in seed coatings, they help maintain moisture around the seed during germination. This localized moisture availability is especially beneficial in dry and semi-arid regions, where short-term water stress can severely limit emergence. Improved germination and early seedling development under drought conditions have been reported with polymer-coated seeds (Li *et al*., 2021).

2.4 Nano-Based Seed Coatings

The use of nanotechnology in seed coating has introduced materials that enhance nutrient delivery and influence physiological responses during germination. Nano-based coatings have been shown to improve early seedling growth under salinity, heat, and moisture stress by improving nutrient efficiency and stress tolerance mechanisms. However, careful evaluation of their environmental safety is essential before large-scale adoption (Kah *et al*., 2019).

2.5 Biological and Bio-Stimulant Coatings

Seed coatings can also be used to deliver beneficial microorganisms and natural bio-stimulants. Microbial coatings support nutrient uptake and improve plant tolerance to environmental stress, while bio-stimulants such as humic substances and antioxidants promote root development and seedling vigor. These biological approaches enhance early plant establishment under unfavorable growing conditions (Berg & Raaijmakers, 2018).

3. Mechanisms Supporting Stress Tolerance

Seed coatings enhance seed performance through multiple interacting mechanisms. Moisture-retaining materials reduce dehydration during germination, while nutrients and growth-promoting substances are released in a controlled manner to support early development. Some coatings strengthen antioxidant defense systems, helping seedlings cope with oxidative stress, whereas microbial coatings improve root activity and nutrient availability. Together, these effects improve germination success and seedling survival under climatic stress (Paparella *et al.*, 2015).

4. Role in Climate-Resilient Agriculture

Seed coating technologies contribute to climate-resilient agriculture by improving crop establishment and reducing the risk of early crop failure. Coated seeds generally show better performance under unfavorable environmental conditions, making them particularly useful in rainfed and marginal farming systems. Targeted delivery of inputs also minimizes wastage and supports environmentally sustainable production practices (Farooq *et al.*, 2019).

5. Challenges and Future Directions

Despite their benefits, seed coating technologies face several challenges, including higher formulation costs, limited long-term field validation, and environmental concerns related to certain coating materials, especially nano-based products. Future research should emphasize biodegradable coating materials, large-scale field testing, and the development of clear regulatory guidelines. Integration of seed coating with other climate-smart agricultural practices could further enhance its effectiveness and adoption (Pedrini *et al.*, 2017).

6. Conclusion

Seed coating technologies provide a flexible and efficient approach to improve seed performance under changing climatic conditions. Advances in polymer science, biological inputs, and nanotechnology have expanded their role in sustainable agriculture. With appropriate evaluation, regulation, and farmer-oriented application, seed coating can play a significant role in strengthening climate-resilient seed systems.

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