Biopriming Strategies for Improved Seed Germination in Nutrient-Poor Environments: A Comprehensive Review

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Abstract

Biopriming is a promising technique that involves treating seeds with beneficial microorganisms, biostimulants, or nutrients to enhance germination, growth, and stress tolerance under various environmental conditions. This comprehensive review evaluates the potential of biopriming strategies to improve seed germination in nutrient-poor environments. We discuss how biopriming enhances germination, including improved water uptake, nutrient assimilation, and resistance to abiotic stress. Additionally, we examine different biopriming agents, such as beneficial bacteria, fungi, and biofertilizers, and their effects on seed germination and plant health. Case studies from various crops and agricultural systems are reviewed to illustrate the benefits and challenges of biopriming. Our analysis highlights the potential for biopriming to promote sustainable agriculture in nutrient-deficient soils and presents future research directions for optimizing this technique.

Keywords: Biopriming, seed germination, nutrient-poor environments, beneficial microorganisms, biostimulants, nutrient assimilation, abiotic stress resistance, sustainable agriculture, biofertilizers, plant health

Introduction

Seed biopriming is a seed treatment technique that integrates biology (seed inoculation) with a beneficial organism to protect the seeds) and the physiological aspects of disease control. It is an ecological approach that uses selected fungal antagonists against soil and seed pathogen transported. Biological seed treatment can provide an alternative to chemical control. Seed bioprimation has been used commercially in many vegetable crops to grow germination speed and uniformity and improve the final position. Biopriming has great promise to improve the efficacy, shelf life, and constant performance of biological control agents (Callan *et al*., 1997; Toribio et. al., 2021). This methodology is used commercially in many horticultural crops, as a tool to increase the speed and uniformity of germination and increase the final stand. Biopriming has great promise to increase the efficacy, shelf life, and consistent performance of biological control agents. Seed care is more effective and economical than wetting because it requires a small volume of inoculum**.**

Biological seed treatments offer an alternative to chemical control, with additional benefits of resistance to induced diseases, ecological nature, and sustainable disease management. *Trichoderma virides*, *Trichoderma harziI* certain, and *Pseudomonas fluorescence* are different biocontrol agents commonly used for the treatment of biopriming. Several researchers have investigated the use of beneficial microorganisms in the priming environment to control the proliferation of the disease during priming (Warren & Bennet 2000). Germination was expressed as a percentage of the ratio of normal seedlings to the sum of normal, abnormal, and unsold seeds, that is, total sown seeds. (Hare and Bale, 2000; Miljaković et. al., 2021). This promising seed biological treatment method provides reduced tolerance to stress before seeding.

Biopriming in combination with hydroprimation has become a viable treatment for increasing seed germination rate and seedling vigor. When planted, primed seeds usually appear faster with better, uniform, and vigorous vegetation cover and remain stable even under conditions that do not correspond to optimal fields (Rehman *et al*., 2011). Seed-related diseases are specific plant diseases transmitted from seeds. They are responsible for a significant loss of productivity of various crops because of nutrient deficiency. Pathogens may be present on the seeds outside or inside and cause infection during or before germination. To increase the production of agricultural yield qualitatively and quantitatively it requires vigorous and quality seeds, with a high percentage of germination and disease-free (Sarkar et. al., 2020; Angelika et. al., 2023).

Stress increases the production and productivity of the exchange rate induction process of physiological and biochemical processes. The reduction of growth under stress conditions is a beneficial state in several species of species, such as rice, barley, maize, and wheat (Kasim *et al*., 2013). The biological method can overcome seed-borne disease, which is the best alternative to chemical methods as they use various biocontrol agents that provide protection to seed forming with the coat of antagonists and are safer for the environment and human health. Seed priming is an important tool to improve the emergence of crops, especially under stress conditions (Pill *et al*., 2009; Rakshit *et al*., 2014). In their study, Pawar & Laware (2018) discussed seed priming technology that can synchronize seed germination and improve vigor, leading to better crop production and yield. The priming of the seeds stimulates the processes involved in the metabolism which prevents the deterioration of the seeds, breaks dormancy, and induces systemic resistance against biotic and abiotic stress.

The biocontrol agent layer is applied on the seed surface as a protective coating or biological treatment of the seed.

- Must have high rhizospheric competence.
- It should improve plant growth as a result of protecting seeds and roots from pathogens
- It must improve plant nutrition by producing growth-stimulating substances.
- Non-pathogenic to host plants and environment
- It should be cheaper for large-scale production.

Need and Significance of Biopriming Research in Nutrient-Poor Environments

Extensive studies to identify new genres and species suitable for bio-priming. Microbes produce various metabolites that act as signals during stress conditions and plants have a mechanism to recognize certain compounds released by microbes and activate defense mechanisms in response to stress conditions. Plant-associated microorganisms are not only involved in stress tolerance but also regulate plant growth and development.

The productive efficiency of bio-priming of specific microbes may be further enhanced with optimization and acclimatization according to the prevailing soil conditions. In the future, they are expected to replace chemical fertilizers, pesticides, and artificial growth regulators that have numerous side effects for sustainable agriculture. Researchers should study the effectiveness of bio-agents in other manifolds like abiotic factors. Increase compatibility with chemical pesticides. Exploration of possibilities in utilizing various microbes for bio-priming of seeds.

The effects of various abiotic and biotic elicitors on secondary metabolite production in plant tissue cultures are dependent on the specific secondary metabolites. The exploration of the production of useful secondary metabolites through regulation of the biosynthetic pathway of the various plant cell and tissue cultures of medicinal plants has been carried out by a group of plant scientists. The microbes can be applied to improve the growth and productivity of plants, with the potential to be used for genetic improvement of nutrient deficiency. However, for genetic improvement to be achieved, a solid understanding of the physiological and biochemical changes in plants induced by microbes is required. The study will carry out the effect of microbes on the physiology and biochemical changes in plants grown under stress conditions and their association with nutrient uptake mechanisms. The stress resistance microbes lead to efficient microbial formulation/Biopriming for boosting the plant performance and substantially reducing the use of chemical fertilizers and pesticides.

The study emphasizes the accumulation of secondary metabolites under abiotic stress. The role of such abiotic stress regulate the production of secondary metabolites. The importance of such secondary metabolites is much known as they are found to show antimicrobial, antioxidant, or source of bioactive compounds which are commercially important. The screening of such compounds helps the understanding of their functions under stress conditions following the blending of microbes onto the seed and that enhances plant growth reciprocates and enriches the rate of crop productivity under different abiotic stress

In the bio-primer, the seeds are exposed to limited water under controlled conditions, which leads to the accumulation of solution in the embryo and there will be no germination until the water potential of the embryo reaches the threshold level required for the radical emergency (Bradford 1986). Coating of *Pseudomonas fluorescens* AB254 sweet corn seeds provided an equivalent degree of extinction protection under all conditions except the most severe (Nancy *et al*., 1991).

Bio-priming leads to biochemical changes, i.e., increased production of proteins, hormones, phenol, and flavonoid compounds helps to improve plant growth and developmental performance. The growth responses in herbaceous plants are determined by nitrogen reserve compounds such as nitrates, amino acids, and proteins (Bewley *et al.*, 1990, Volenec *et al.*, 1996).

The technology of seed priming has proven to be important in improving seed quality in promoting plant growth (Aliye *et al*. 2008; Rajkumar *et al*. 2010, 2012). Bio-priming is an integrated method of biological seed treatment and pre-plant hydration or hydropriming (Callan *et al*., 1990). Bacterial seed coating enhanced rapid and more uniform seed germination with vigorous plant growth (Moeinzadeh *et al*., 2010). An increase in the net productivity of biomass, relative water content, and leaf water potential was raised when maize was bioprimed with *Pseudomonas spp*. (Sandhya *et al*., 2010).

Several studies in various agro-ecological situations have confirmed that seed primers have many benefits, including seed dormancy, uniform germination, deeper roots, better resource use, better competition with weeds, early flowering, and maturity, and they grow faster under stress (Bajehbaj 2010) Moeinzadeh *et al*., (2010) studied the effects of 30 fluorescent Pseudomonas strains on improving the germination of sunflower seeds and promoting seedlings growth. After the selection of the effective strains, the efficacy of the treatment of the seeds of biopriming was compared with the treatment of inoculation and priming of the seeds and this one, under the conditions that the biopriming finalized with *Pseudomonas fluorescence* UTPf76 and UTPf86 assured very well the establishment and the adhesion of the bacteria to the seed, before the plant, and thus is suggested as an appropriate treatment for improving seed rates and improving seedling growth.

Bioprimed seeds have an advantage over non-primary seeds at the beginning of the germination process because bio-primed seeds have large carbohydrate storage reserves that strengthen the plant to survive low oxygen stress in flood conditions (M. L. & Ismail 2011). Reddy *et al* (2011) reported the implications of *Pseudomonas fluorescens* improved seedling emergence of chickpeas to 96% and 98% and reduced frequency of dry root rot to 28% and 35%, respectively. This type of beneficial plant-microbe interaction in the rhizosphere has influenced plant vigor and soil fertility by stimulating plant growth through the mobilization of nutrients in soils, the production of numerous plant growth regulators, the protection of plants from phytopathogens controlling or inhibiting them, improving soil structure and bioremediating polluted soils by sequestering toxic heavy metal species and degrading xenobiotic compounds (such as pesticides(Bhattacharyya & Jha 2012).

Ahemad & Khan (2012) reported that the nitrogen-fixing PGPR may be symbiotic such as diazotrophs (a form of non-obligatory interaction) and rhizobia (a form of nodules) and non-symbiotic such as azospirillum, nitrogenbacter, and cyanobacteria, etc. Several numbers of seed technologies (priming, pelleting, coating, etc.) have been extensively used to combat many challenges and enhance germination and synchronization of seedling emergence under adverse environmental conditions of abiotic stress have been developed (Rakshit *et al*. 2013; Roy and Srivastava 2000; Ashraf *et al*. 2011; Basra *et al*. 2005; Tzortzakis 2009).

In the study (Baral & Adhikari, 2013), it was reported that seed inoculation with Azotobacter sp. increased 35% grain yield in maize over non-primed treatments. The function of various rhizomicrobials belong to the genera Pseudomonas, Azotobacter, Rhizobium, Azospirillum, Pantoea, Bacillus, Enterobacter, Bradyrhizobium, Burkholderia, Trichoderma, and Cyanobacteria in plant growth and the fight against different environmental challenges (Sahoo *et al*., 2014).

Dhawal *et al*., (2016) stated that beneficial microbes such as *Arbuscular mycorrhizae* when used as a seed treatment can produce strong and healthy plants and induce significant effects in rhizospheric soils. Therefore, the concept of bio-priming is very important for the development of sustainable agriculture practices.

In vitro, bioprimination of chili seeds revealed priming of *P. fluorescens* seeds. At 10 g / kg of seeds, a maximum seed germination rate of 86.70% was recorded than with another proven treatment, but this was statistically at the level of *T. harzianum* used when absorbed, and the minimum percentage of infected P. seeds fluorescence is used when absorbing 21.3% (Chauhan and Patel 2017).

Monalisa *et al*., (2017) reported that seed biopriming with Trichoderma harzianum and 40% Pseudomonas fluorescence concentration for 4 hours improves seed quality parameters. Biopriming of the seeds with *Trichoderma harzianum* for 4 hours of soaking gave better results in terms of germination (78%), seedling length (50.2 cm), dry weight of the plant (2.25 g), SVI-(3889. 6), SVI-II (174.7) and the speed of the germination index (9.2). Therefore, it can be inferred that the *Trichoderma harzianum* in applied condition was found to be the best for improving the quality parameters of the seeds in the common bean.

Sivakalai & K. Krishnaveni (2017) concluded that the performance and impact of bioprimed seeds under field conditions brought out the positive influence of seeds bioprimed with Azospirillum 10 % + Phosphobacteria 20% + Pseudomonas fluorescens 20% for 12 hours, which maximizes plant growth and development, yield and seed quality. Kabdwal *et al*., (2019) reported that *Trichoderma harzianum* (Th43), *Pseudomonas fluorescens* (Pf173), Jas mycorrhiza (AMF), and fungicide (Mancozeb) in the various combinations used by tillage, seedling treatment, and leaf spraying were evaluated for growth promotion and control of tomato diseases in experimental and farmer fields, which stimulates different growth parameters and makes them more sustainable

Promising Bio-inoculants for Seed Biopriming

The secondary metabolites released by the rhizobacteria and by the interactions of the root system of the plants, increase the availability of nutrients for the plants with a better nitrogen fixation capacity of the plants and improve the greeting of the plants through biocontrol of the pathogens of the plants (Sturz & Christie, 2003). The population of Azotobacter is generally low in the rhizosphere of cultivated plants and uncultivated land. The presence of this organism has been reported by the rhizosphere of a series of cultivated plants such as rice, corn, sugar cane, bajra, vegetables, and plantation crops (Arun 2007).

Sakthivel *et al*., (2009) reported the impact consortium treatment of (Pseudomonas + Azotobacter + Azospirillum) has increased fruit yield in tomato variety PKM-1. Baser-Kouchebagh *et al*., (2013) showed that biopriming with Azospirillum, Azotobacter, and Pseudomonas sp, increases the crop growth rate, yield, and quality of medicinal plants. Sakthivel *et al*., (2009) reported the impact consortium treatment of (Pseudomonas + Azotobacter + Azospirillum) has increased fruit yield in tomato variety PKM-1. In soybeans, biopriming with *Pseudomonas aeruginosa* was found to be an effective treatment for controlling the dampening of pre- and post-emergence soybeans (Begum *et al*., 2010).

Shirinzadeh *et al*., (2013) studied that barley seeds primed with A*zotobacter*, *Azospirillium*, and its consortia (*Azotobacter* + *Azospirillium*) could increase plant and spike height, spike number/area, grains/spike, and grain yield, and weight. Therefore, the potential for using

Azotobacter spp. as a biological agent for the production of fertilizers from the spent washing of sugar cane is currently considered globally (Dawood et al., 2005; Patil *et al*., 2013).

Rodriguez (2015) concluded three species of plant growth that promote rhizobacteria (*Pseudomonas fluorescens*, *P. putida*, and *Bacillus subtilis*) and it was found that the use of hydropriming and biopriming with PGPR bacteria improved the germination rate of *A.religiosa* and *A. Hickelii* in greenhouse conditions. *P. fluorescens*, *P. putida*, and *B. subtilis* are potential tools to promote biological germination in *A. religiosa* and *A. hickelii* and growth at least in *A. hickelii.*

In the study of (Kumar *et al.,* 2015), two bioagents *Trichoderma harzianum Th.azad* and *Trichoderma virid*e 01PP were evaluated for their effectiveness on the growth of colonies with the double culture plate method. The results showed that the two bio-agents suppressed the growth of the colonies of *Fusarium oxysporum f. sp. ciceri*, ranging between 53.38-57.99%, the suppression of growth of the pathogen was relatively higher with *Trichoderma harzianum Th.azad.*

Benaseer *et al*., (2017) showed the effect of seed priming with biological agents on germination and seedling vigor was evaluated by giving priming treatment with liquid formulation viz., effective micro-organisms, sulfur solubilizing, facultative methylotrophs (PPFM), rhizobium + phosphor bacteria at different concentration of coconut water and cowpea sprout extract and it was observed that all the priming methods showed significant differences with the control and the highest germination (93 %), root length (18.28 cm), epicotyl length (21.15 cm), hypocotyl length (9.76 cm), seedling dry matter production (0.279 g 10 seedlings-1), vigor index (4573) and field emergence (92 %) were observed in the seed primed with PPFM 2%.

Alleviation Mechanism of Stresses in Bio-inoculants

Gibberellin and cytokinin produced by *Azotobacter chroococcum* and *Rhizobium leguminosarum* have an optimistic effect on the height and growth of plants (Verma *et al.,* 2001). Glick (2012) reported that bio-priming with IAA released rhizobacteria by loosening plant cell walls and increasing the exudation of roots from the plant, improving the availability of more nutrients for the microorganism and supporting its growth in the rhizosphere.

Rhizobacteria that promote plant growth (PGPR) are beneficial bacteria that colonize plant roots and improve plant growth through a variety of mechanisms that include improving plant nutrition, the production, and the regulation of phytohormones and suppression of pathogenic organisms (Ngoma *et al.*, 2012).

The trigger also helps improve the function of malate synthase and isocitrate lyase which converts lipids into carbohydrates, while antioxidant enzymes (POD, SOD, CAT, and GR) eliminate ROS (reactive oxygen species). Therefore, protect the seeds from lipid peroxidation and oxidative damage of membrane phospholipids making the longevity of the seeds (Oliveira *et al* 2012).

Wani *et al.* (2013) summarized the possibility of using *Azotobacter chroococcum* in research experiments as a microbial inoculant through the production of growth substances and their effects on the plant have significantly improved agricultural production in agriculture. Being soil bacteria, the genus *Azotobacteria* synthesizes auxins, cytokinins, and GA-like substances, and these growth materials are the primary substances that control improved growth. IAA also acts as a mutual signaling molecule affecting gene expression in several microbes. Consequently, IAA plays a very important role in rhizobacteria-plant interaction. Bacterial species such as Bacillus have been shown to control fungal diseases. Recent reports have shown that they are capable of lysing chitin, which is a major constituent of the fungal cell wall. Also, these bacteria can disintegrate proteins (proteolytic activity) which play a key role in the nitrogen cycle. The mechanism of water absorption in seeds in three stages well explained in three stages; in the first phase imbibition phase, in which a rapid absorption of water through the forces pulled by the seeds and metabolic changes occur. In the second phase, there is less water intake with a consequent slight increase in the fresh weight of the seeds. This phase is also called the activation phase which helps to mature mitochondria (causing ATP synthesis), protein synthesis from new mRNAs, and mobilization of macromolecules stored in molecules necessary for radical growth. The third germination stage in which the growth of the seedling begins with the resumption of the root and rapid absorption of water. Because of this, various benefits are imposed on the seeds such as the synchronization of the emergence of the radicles, the increase in the growth rate, and the improvement of a large number of seeds to germinate. This reduces the time required for cellular activities. The DNA content increases due to the activation and/or synthesis of nucleic acid enzymes, eventually increasing the total amount of RNA and proteins. It also heals damage to the cell membrane during preservation (Dalil 2014, Varier *et al.*, 2010 Selvarani & Umarani 2011).

Several microbes induce plant responses that alter the level of many defense proteins, antioxidant enzymes, polysaccharides, and phytohormones, (Pandey *et al*., 2016).

Bioprimination was also found to cause the early synthesis of DNA and protein. It was reported that bioprimination enhances the expression of the RuBisCO and chl a / b genes, expansins, β-tubulin, and GST, resulting in the ability to carboxylate and efficient photosynthesis, which stimulates the process of early germination and intensive plant growth (Sukanya *et al*., 2018).

Biopriming under Nutrient deficiency

Micronutrients act as cofactors in enzyme systems and are involved in redox reactions, in addition to having several other vital functions in plants. Most importantly, trace elements are involved in the basic physiological processes of photosynthesis and respiration (Marschner, 1995; Mengel et al., 2001), and their deficiency can interfere with these vital physiological processes, thereby limiting yield growth. Puertas and Gonzales (1999) reporting the dry weight of the tomato plants inoculated with *Azotobacter chroococcum* and cultivated in phosphate-deficient soils, was greater than that of the non-inoculated plants. Phytohormones (auxin, cytokinin, and gibberellin) can stimulate root development. Microorganisms are involved in many natural processes, such as the nutrient cycle (Nannipieri et al., 2003), biological control of plant pathogens (Handelsman & Stabb, 1996; Saba et al., 2012), and the creation, development, nutrition, and health of plants (Linderman, 1992), who expected an increase in recognition in agriculture. In crops, micronutrients can be applied to the soil, sprayed on foliage, or added as a seed treatment. Although the required amount of micronutrients can be obtained by any of these methods, leaf spraying has been more effective in improving yield and enriching grain; but high cost limits its wider adaptation, especially to poor farmers (Johnson et al., 2005).

Seed bio-priming with liquid biofertilizers (azospirillum and phosphobacteria) improved the germination rate, the total germination rate, the growth of the seedlings, and vigor in the chili pepper (Ananthi *et al*., 2014). Seed inoculation with Azotobacter increased wheat yield by 35% in maize compared to uninoculated treatments (Baral & Adhikari, 2013). Ananthi *et al*., (2014) concluded the consortium effect of seed bio-priming with liquid biofertilizers (Azospirillum and Phosphobacteria) enhanced the germination rate, total germination percentage, seedling growth, and vigor in chili. Water stress can occur simultaneously with the S deficiency in cultivation systems with low fertilizer intake, the impact of the combined deficiency Recent studies have highlighted the fact that the response of the plant to a combination of two abiotic stresses is unique and that the result of interaction cannot be extrapolated from the effects of individual stresses (Pandey *et al*., 2015; Zhang and Sonnewald, 2017).

Plant growth regulators can be used to improve yields in terms of yield and seed nutrition by modulating plant growth and physiological processes such as photosynthetic efficiency and dynamics of nutrients in the plant (Khan *et al*., 2005; Anjum *et al*., 2016). Some studies have argued that exogenously applied PGRs improve crop productivity and crop nutrition by improving photosynthesis and absorption of nutrients and accumulation in plants (Nagel & Lambers, 2002; Agegnehu & Taye, 2004; Niu *et al*., 2016).

(Nagalla *et al*., 2017) evaluated the growth rates of *Azotobacter chroococcum* and *Azotobacter vinelandii*, two species. Commonly found in the sugarcane rhizosphere, in two broth cultures: tryptic peptone broth (TPB) and liquid glucose broth (LGB) using optical density (OD) measurements at a wavelength of 620 nm over an incubation period of 12-15 hours. *Azotobacter chroococcum* had a higher growth rate than *A. vinelandii,* especially in TPB. Despite the cost, the *A. chroococcum* inoculum grown in TPB can be recommended for commercial production of biofertilizers due to its yield and time advantages.

Jainapur *et al*., (2018) reported that the *P. fluorescens* treatment at 0.8% + *T. harzianum* at 0.8% + Vermiculite showed the minimum seed infection of 13.00%, the highest seed germination of 91.00% and a vigor index of 1753.13 which was statistically higher than other treatments. Charlotte *et al.,* (2019) investigated wheat legume (*Pisum sativum*), the sulfate was exhausted in the medium vegetative phase and during the first reproductive phase, a moderate period of water stress was imposed. The combination of stresses prevented reproductive processes synergistically, reducing the weight and number of seeds and inducing seed abortion, which highlighted the fundamental importance of sulfur to keep the seed yield components under water stress.

Conclusion

Bio-priming improves overall plant growth and development by physiological, biochemical, and molecular level alteration which in the end results in an asset to modern agriculture. Bio-priming also improves the total soluble sugar, reduced sugar content, total protein content, and ATP production in the plant leading to optimum plant growth-priming can provide a high level of protection against seed and soil-borne diseases that can be almost equal to or even superior to chemical treatment Bio-priming can protect the seed and soil-borne diseases which can be almost equal or even higher and safer to the chemical treatment. So, farmers should be encouraged to adopt it which helps in safe production and an increase in yield with minimal environmental and health hazards. Seeds are a source of life so let's start protecting it biologically rather than with chemicals. This is particularly interesting for organic farmers because it is difficult to produce high-quality disease-free seeds organically.

To ensure the high efficacy of inoculants and biological fertilizers, it is essential to find compatible partners, i.e. a specific plant genotype and a particular microbial species that will form a beneficial association. Seed bioprimation is a very effective method for seed treatment which ultimately leads to improved plant growth under nutrient deficiency The increase in the experiment to determine the optimal soaking period in the suspensions of biocontrol agents with rhizobacteria revealed that the advantage of priming and quality parameters of seeds such as germination, length of shoots, length of roots, strength index and germination index. Seed priming is an important tool to improve the emergence of crops, especially under stress conditions and strain has the potential to manipulate IAA concentrations in its interaction with plants and to stimulate plant growth as seed inoculants. Plants depend on the potential and expansion of roots to communicate with microbes.

The use of microbial strain commercial scale may, therefore, improve crop yields in agricultural applications. With the help of ongoing formulation experiments, we seek to develop cost-effective formulas to replace the expensive nitrogen, phosphorus, and/or potassium-containing commercial fertilizers that are frequently used in agriculture today

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