Microbial seed coating: an attractive tool for sustainable agriculture

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Abstract

Today, the issue of crop yield and quality is one of the many challenges facing societies. Residues of pesticides, chemical fertilizers, hormonal compounds, and preservatives have caused many environmental issues. It is necessary to reduce these environmental crises by paying attention to the development of sustainable agriculture. Seed coating is considered one of the best methods to promote sustainable agriculture where the physical and physiological properties of seeds can be improved to facilitate planting, increase growth indices and alleviate abiotic and biotic stresses. Several methods of seed coating (e.g., dry powder coating, seed dressing, encrusting, seed pelleting, and film coating) are used to attain good application uniformity and adherence in the seed coating process. Seed coating has been tested in seeds of various plant species (e.g., vegetables, medicinal and other plants with small seeds) with different dimensions, forms, textures, and germination types. Plant beneficial microorganisms (PBM), such as rhizobia, bacteria, and fungi inoculated via seed inoculation can increase seed germination, plant performance and tolerance across biotic (e.g., pathogens and pests) and abiotic stress (e.g., salt, drought, and heavy metals) while reducing the use of agrochemical inputs. In this review, the microbial seed coating process and their ability to increase seed performance and protect plants from biotic and abiotic stresses are well discussed and highlighted in sustainable agricultural systems.

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Abstract

Today, the issue of crop yield and quality is one of the many challenges facing societies. Residues of pesticides, chemical fertilizers, hormonal compounds, and preservatives have caused many environmental issues. It is necessary to reduce these environmental crises by paying attention to the development of sustainable agriculture. Seed coating is considered one of the best methods to promote sustainable agriculture where the physical and physiological properties of seeds can be improved to facilitate planting, increase growth indices and alleviate abiotic and biotic stresses. Several methods of seed coating (e.g., dry powder coating, seed dressing, encrusting, seed pelleting, and film coating) are used to attain good application uniformity and adherence in the seed coating process. Seed coating has been tested in seeds of various plant species (e.g., vegetables, medicinal and other plants with small seeds) with different dimensions, forms, textures, and germination types. Plant beneficial microorganisms (PBM), such as rhizobia, bacteria, and fungi inoculated via seed inoculation can increase seed germination, plant performance and tolerance across biotic (e.g., pathogens and pests) and abiotic stress (e.g., salt, drought, and heavy metals) while reducing the use of agrochemical inputs. In this review, the microbial seed coating process and their ability to increase seed performance and protect plants from biotic and abiotic stresses are well discussed and highlighted in sustainable agricultural systems.

Keywords: Beneficial microorganisms, Agricultural sustainability, Delivery systems, Seed coating, Seed

quality.

Abbreviations

PBM: Plant beneficial microorganisms, PGPB: Plant growth-promoting bacteria, AMF: Arbuscular mycorrhizal fungi.

Introduction

Conventional agriculture is large-scale agriculture that widely uses artificial fertilizers, herbicides, and pesticides (Razanakoto et al. 2021). As an alternative, sustainable agriculture is fixed on management planes addressing the main societal worries about food quality or environmental protection. It involves two approaches: 1) agriculture should keep itself over a long period by conserving its productive resources, such as soil fertility maintenance, protection of groundwater, development of renewable energies, and detection solutions for acclimating farming systems to variations of climate; 2) agriculture systems should aid the sustainability of large domains and social societies (Lichtfouse et al. 2009). Nowadays, without reducing the yield and quality of crops, the agricultural systems should apply minimum inputs and resources to attain economic advantagability, environmental security and social justice (Le Bail et al. 2005). During the past ten years, the world population has considerably enhanced and is envisaged to attain around 9.5 billion by 2050 (Singh et al. 2016). Therefore, given the growing global population, achieving global food security is possible through the design of advanced agricultural systems that can maximize our productivity and production with the minimum input required (Berg 2009). The additions contain phosphorus and nitrogen as fertilizer and pesticides as biocontrol agents for invasive weeds, pathogens, and insects. To increase or maintain crop yield, the farmers can benefit from new sustainable products, such as plant beneficial microorganisms (PBM) (Baulcombe et al. 2009).

The soils are considered the densest and most diverse microbial habitats of plants (Fierer and Jackson 2006). Plant roots interact closely with soil micro-organisms. Complex interactions between roots and their related microbiomes are key factors in plant health (Mauchline and Malone 2017). The soil-borne pathogens limit and reduce plant growth, while the association of plants with PBM can promote plant growth. These PBM can facilitate plant nutrient uptake or increase stress tolerance (Pieterse et al. 2016). In addition, they can protect plants against pathogens through antagonism, competition, and stimulation of the plant's immune system (Pieterse et al. 2016). PBM include rhizobia associated with legumes and mycorrhizal fungi, as well as other free-living plant growth-promoting bacteria (PGPB) and fungi (PGPF) that and fungi (PGPF) that benefit a broad variety of plant species (Berendsen et al. 2015). PBM can increase plant growth, facilitate water and nutrient uptake and distribution through different mechanisms (Allen 2009). For example, mycorrhizal symbiosis in soils may help to absorb and transfer water and nutrients through hyphae from the outer mycelium (Maurel and Chrispeels 2001). PGPB can help establish a root system and enhance plant growth by synthesizing bioactive substances such as phytohormones (e.g., auxins, gibberellins, and cytokinins), siderophore, and 1-aminocyclopropane-1-carboxylase (ACC) deaminase (Maurel and Chrispeels 2001). Moreover, nitrogen fixation through PBM occurs in free-living or non-coexistence (e.g., *Azotobacter*), coexistence (e.g.,*Rhizobium*), and cooperation (e.g., *Azospirillum*) forms (Malusá et al. 2012, Rocha et al. 2019a).

In the 1930s, the first seed coating artificial on cereal seeds was inspired by the pharmaceutical industry, and thereafter the using large-scale commercial of this tool started in the 1960s (Kaufman 1991). Nowadays, this tool was availed worldwide in horticultural and crop industries (Rocha et al. 2019a). In the artificial seed coating, different materials (e.g., biopolymers, colorants, biocontrol agents, and microbes) are used in coating the surface of seeds (Piri et al. 2019, Rocha et al. 2019a) to correct the physical features of seed crops and vegetable species, turfgrass, pasture, and flowers via deformation of seed weight and size (Afzal et al. 2020). The function of seed coating according to its mode of action or properties includes protecting plants, reducing environmental stress, or improving plant growth (Amirkhani et al. 2016). Indeed, seed coating is used as a biological tool that improves follow ability for agricultural sustainability (Piri et al. 2019, Rocha et al. 2019a). Considering these advantages, nowadays the application of this tool has been proposed for seed inoculation in different plants since it can use partial rates of inocula in a precise use (Rouphael et al. 2017). Hereby, the purpose of this study is to examine microbial seed coatings and their significance for sustainable agriculture.

Plant beneficial microorganisms

Types of PBM

PBM are known as microorganisms that can increase plant establishment, growth and development, and defend plants across disease and abiotic stresses. PBM mainly include PGPB, arbuscular mycorrhizal fungi (AMF), and rhizobia.

Plant growth-promoting bacteria

The most PBM present in soils are PGPB such as *Azospirillum* ,*Azotobacter* , *Pseudomonas* , and *Bacillus* , which are bacteria capable of inducing growth and development of plants and protecting plants against phytopathogens (Rocha et al. 2019b). PGPB increase plant tolerance to environmental stresses and facilitate plant growth through direct and indirect mechanisms. Direct mechanisms by PGPB include expanding root growth, fixation of atmospheric nitrogen (Bloch et al. 2020), solubilization of mineral nutrients (e.g., phosphate, potassium) (Adnan et al. 2020), and production of phytohormones (e.g., auxins, cytokinins, and gibberellins) (Sudewi et al. 2020), iron-chelating siderophores (Kramer et al. 2020), and organic acids. Indirect mechanisms can be neutralized or modify the harmful effects of plant pathogens by producing various antagonistic compounds, such as extracellular lytic enzymes, hyperparasitism, antibiotics, siderophores, and hydrogen cyanide (Emmanuel and Babalola 2020).*Bacillus* sp. such as *B. amyloliquefaciens* , *B. subtilis* , and *B. sphaericus* can breed resistance in plants against viral diseases (e.g., cucumber mosaic virus on tomato) (Kloepper et al. 2004).

Arbuscular mycorrhizal fungi

In agricultural and natural ecosystems, as biologically beneficial fungi, AMF can create an interaction of physical between plant roots and soils, which represent an essential part of agricultural ecosystems (Khan 2005). Nearly 90% of AMF can form symbioses with plant roots (Ortas and Bykova 2018, Paravar et al. 2022), contributing significantly to increasing plant uptake of macro and microelements in soils under environmental stress (Ghanbarzadeh et al. 2020) and to improving soil density to create a protective barrier from pathogens and enhance water acquisition (Rocha et al. 2019a). AMF can also protect crops against environmental stresses (Langeroodi et al. 2020). For instance, under drought stress, AMF may increase plant water uptake and turgor maintenance associated with osmotic balancing, and root hydraulic conductivity (Langeroodi et al. 2020, Zou et al. 2020). Overall, AMF play a beneficial role in producing metabolites such as essential oil (Pirzad and Mohammadzadeh 2018), fatty acids (Rahimzadeh and Pirzad 2019), phytohormones (Kadam et al. 2020), amino acids (Zhang et al. 2020), antioxidant enzymes (Piri et al. 2019, Zou et al. 2020), and adjusting plant physiological statuses such as carbon dioxide exchange amount (Thirkell et al. 2020), stomatal conductance (Boutasknit et al. 2020), photosynthetic pigments, proline content (Alam et al. 2019), and phenolic content (Bencherif et al. 2019). It has been demonstrated that AMF can enhance photosynthesis activities and stomatal movement by developing the root systems (Gholinezhad and Darvishzadeh 2021). Indeed, root colonization by mycorrhizal mycelium not only bolsters the root systems but also facilities the absorption of water and nutrient from larger soil volumes against drought stress (Paravar et al. 2021). Additionally, a raised nutrients uptake especially phosphorous by developing root system can provide the essential ATP and NADPH, which support oil and fatty acids biosynthesis (Rezaei-Chiyaneh et al.

2021). Some researchers reported that AMF can decrease the accumulation of ROS by increasing flavonoids, carotenoids, anthocyanins, and phenols under water deficit (Jerbi et al. 2022).

Other beneficial microorganisms are *Trichoderma*(Coninck et al. 2020) which can be applied as biological control generalists of plant diseases and pathogenic fungi with a well-shielded cropping system (Yang et al. 2017). They can control pathogens by absorption of released nutrients (known as mycoparasitism) (Kim et al. 2021), production of antibiotics (e.g., aldehydes, alcohols, ketones, hydrogen cyanide, and heterocyclic nitrogen) (Daryaei et al. 2016), and generation of degrading enzymes (e.g., crystalline cellulose-hydrolyzing enzyme and b-glucosidase) in the cell wall (Kthiri et al. 2020). *Trichoderma*species can colonize the rhizosphere at the critical "early germination" stage, contributing significantly to improving nutrient uptake and plant resistance to various stresses (e.g., heavy metal, salt, and drought stresses) (Lutts et al. 2016) and they can serve as usual fungi of soil and rhizosphere to replace chemical seed treatment (Kthiri et al. 2020).

Microbial consortia

Association between microorganisms and host plants can keep soil fertility and plant health, especially in low-input agriculture, which depends on biological prices than agrochemicals (Sessitsch and Mitter 2015). Indeed, in the microbial consortium, microbial species can perform synergistic interaction and give benefit each other. Some strains can maintain the non-producing strains against drought stress by producing secondary metabolites, such as exopolysaccharides (Lau et al. 2022). A study showed that microorganisms belonging to the roots of grapevine and olive plants can improve the growth of *Orize sative* L. This enhancement may be due to the extensive roots system and increased water uptake ability (Yoolong et al. 2019). In addition, it has been found that using humic acid and PGPR (*B.megaterium* and*B. subtilis*) enhanced the plant height and yield compared with untreated control. Indeed, Humic acid and PGPR enhanced the photosynthesis process by promoting stomatal conductance and stomatal density, thereby, improving the yield (Ansari et al. 2019). Also, it has been reported that the application of PGPB and N-fixing bacteria caused the improvement of root growth and resilience of plants against environmental stresses, as well as decreased N losses (Dal Cortivo et al. 2017) PGPB can be used in the formation of ameliorating nodules in legumes when co-inoculated with rhizobia (Rocha et al. 2019a). It has been found that *Bacillus polymyxa* and*Azospirillum brasilense* increased root colonization by*Glomus aggregatum* , and promoted biomass and phosphorus amount of palmarosa grass grew under irresoluble inorganic phosphate source (Oliveira et al. 2017).

PBM inoculation on plant growth

Nutrients

Mixed or separate microorganisms can be inseminated within leaves, seeds, seedlings, roots, or soils. These inoculations cause the colonization of the rhizosphere or the inside of the plant, as well as, growth and toleration across abiotic stress stimulation (Lopes et al. 2021). PBM inoculation directly improves plant growth and productively, tolerance to abiotic stresses (e.g., drought, salt, and extreme temperatures) by increasing nutrient uptake, producing exopolysaccharides, osmoregulators, and antioxidants, regulating phytohormones (e.g., auxin, gibberellin, cytokinin, abscisic acid, and ethylene) (Lichtfouse et al. 2009) and/or indirectly protect plants against abiotic stresses by inducing systemic resistance, as well as producing siderophore and volatile metabolites (Abhilash et al. 2016). Due to the increase in reactive oxygen species (ROS) production, peroxidation of lipids, free radical accumulation and elevated ethylene production, plant growth is inhibited during drought stress. Hence, the above events resulted in cell death and decreasing in photosynthetic rates and chlorophyll content. Also, PBM inoculation can positively affect germination indices of seed, seedling and early growth characteristics, root development and improve crop biomass and productivity (Moradtalab et al. 2020, Sharma et al. 2012).

It has been proved that PBM can be used as biofertilizers to increase the stock of macro and micro-elements, boost plant growth and decrease the application of chemical fertilization (Ghanbarzadeh et al. 2020). Since the essential nutrients for plants mainly include nitrogen, phosphorus, and iron, among PBM selection tests, nitrogen fixation, phosphate solubilization, and siderophore production are widely investigated (Lopes et al. 2021). One of the essential macro-elements for synthesizing proteins and nucleic acids is nitrogen. It has been reported that PGPB strains such as *Azospirillum* ,*Azotobacter* , *Achromobacter* , *Rhizobium* and*Klebsiella* can fix biological nitrogen via decreasing nitrogen gas (N_2) to ammonia (NH_3) (Souza et al. 2015). Moreover, phosphorus is an urgent plant nutrient for growth, which participates as a structural ingredient of nucleic acids, phospholipids, and adenosine triphosphate (ATP) (Khan et al. 2009, Maleki Farahani et al. 2019). Some PGPB strains such as *Rhizobium* , *Bacillus* , *Pseudomonas* ,*Azotobacter* , and *Azospirillium* can dissolve phosphate and convert insoluble organic and inorganic phosphate into available plant form, which are called phosphate-solubilizing bacteria (PSB)(dos Santos et al. 2020;. Organic acids (gluconic or keto-gluconic acids) produced by PSB along with their carboxyl and hydroxyl ions chelate cations and reduce pH to release phosphorus (Sharma et al. 2013). Furthermore, PGPB act a main role in metabolic and biochemical pathways, especially for biological nitrogen fixation and photosynthesis (Richardson and Simpson 2011). It is known that large proportions of soil-phosphorus remain interlocked in various insoluble forms and are unavailable for plants. PBM can decrease soil pH through execration of organic acids such as gluconate, citrate, lactate, and succinate that leads to the acidification of the surroundings and microbial cells, therefore, phosphorus ions are released by substitution of H^+ for Ca^{2+} (Martinez-Viveros et al. 2010). In addition, iron is one of the essential micro-elements for the biosynthesis of chlorophyll, photosynthesis, and respiration. As a chelator, siderophores have a great specificity to bind iron, continued by the transport and deposit of Fe^{3+} in bacterial cells (Dimkpa et al. 2009).*Burkholderia* , *Enterobacter* , *Grimontella* , and*Pseudomonas* can be used as siderophore producers to promote plant nutrition and inhibit phytopathogens via sequestration of free environmental iron (Souza et al. 2015).

Phytohormones

Phytohormones are organic compounds that are responsible for plant development. PBM can modulate phytohormones, such as auxins, cytokinins, gibberellins, abscisic acid, ethylene, salicylic acid, brassinosteroids, jasmonates, polyamines, and strigolactones (Santner et al. 2009). A study reported the increased auxin and gibberellin in leaves of *Zea mays*inoculated by PGPB (Khan et al. 2016). The negative effects of drought, chilling, heat, or salinity stress can be alleviated by PBM inoculation via auxin production, gibberellin, cytokinin, ACC deaminase, abscisic acid strigolactones, and jasmonates (Khan et al. 2020). It has been demonstrated that PBM inoculation increased auxin concentration in plants and improved the growth of various plant species (e.g., *Zea mays* , *Brassica juncia* , *Fagopyrum esculentum* , and*Saccharum officinarum*) by improving uptake of water and nutrient (Gouda et al. 2018). The auxin produced by PBM is a beneficial phytohormone that regulates cell division (Sarkar et al. 2017). PBM can improve plant-related parameters (e.g., seed germination, development of leaves, stem, flower and fruit) by enhancing gibberellin (Zerrouk et al. 2020). Under saline conditions, PBM inoculation can increase the concentrations of abscisic acid, jasmonates, and brassinosteroids in plants (Arora et al. 2020).

Exopolysaccharides

Microorganisms can form a productive biofilm on the root surface by producing exopolysaccharides (Banerjee et al. 2019). In this way, this mechanism causes the increase of water keeping in soil particles and maintains soil moisture in the rhizosphere. In addition*, Streptococcus epidermidis* can protect the cells of plant roots against osmotic stress and enhance environmental stress tolerance (Banerjee et al. 2019). It was suggested that *Pseudomonas putida* strain GAP-P45 as an exopolysaccharide producing bacterium can cause the biofilm formation on the root surface in *Helianthus annuus*seedlings and increase tolerance of seedlings against drought stress (Naseem et al. 2018). In addition, other studies have demonstrated that proline accumulation, sugars and free amino acids increased in plants inoculation by exopolysaccharides producing bacterium *Pseudomonas aeruginosa* and*Azospirillum* spp. under drought stress (Bano et al. 2013, Gusain et al. 2015, Rana et al. 2020).

Antioxidants

The PBM can enhance antioxidant enzymes activities such as ascorbate peroxidase (APX), catalase (CAT) and superoxide dismutase (SOD), and antioxidant non-enzymes such as glutathione (GSH), carotenoids, tocopherols, and phenolics to alleviate ROS accumulations that are caused by various stresses (Fazeli-Nasab et al. 2021, Gouda et al. 2018). Increased activity of CAT and APX due to inoculation of *Cuminum cyminum* seeds with *Pseudomonas fluorescens* and *Trichoderma harzianum* under drought stress conditions has been reported (Piri et al. 2019). *Linum usitatissimum* inoculation with *P. fluorescens* enhanced antioxidant enzymes such as CAT, APX, and GSH in storage conditions (Gafsi et al. 2006).

Osmoregulants

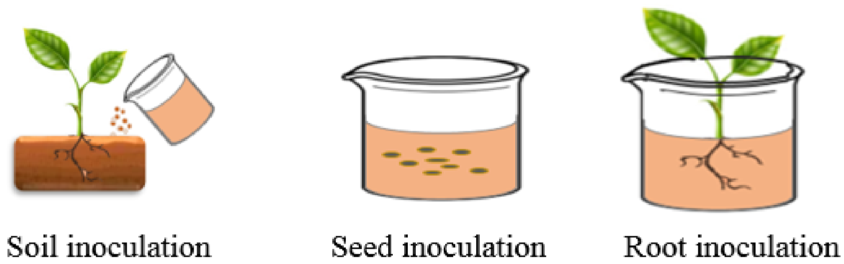
Against drought and salinity stresses, microbial inoculants can produce osmoregulants such as carbohydrates, proteins, amino acids lipids, proline, glycine betaine, and trehalose (Van Oosten et al. 2017). Osmoregulants induce the stabilization of protein and membrane structure under dehydration conditions, maintain osmotic balance across the membrane, and ensure protein correct folding under salinity stress (Sharma et al. 2012). It has been found that *Burkholderia phytofirmans* . can increase plant tolerance across low temperatures by modifying carbohydrate metabolism (Fernandez et al. 2012). Also,*Pseudomonas fluorescens* has been found to promote plant tolerance against water stress by enhancing catalase and peroxidase enzyme activities and proline accumulations (Saravanakumar et al. 2011).

Inoculation methods of PBM

Different methods of PBM inoculation on host plants can affect the survival and reproduction of microbes crowded into the rhizosphere and their ability to promote plant growth (Strigul and Kravchenko 2006). Due to the fact that the mobility of microorganisms in the soil is low, microbial inoculants should be placed in the vicinity of the rhizosphere. To spread microbial inoculants around the rhizosphere, nematodes can be used as a vector for their inoculation (Msimbira and Smith 2020). Except for inoculant density and methods of inoculation, the response of the plant to PBM inoculation and their colonization is also important for microbial functioning (Venturi and Keel 2016). After inoculation, the reduction of microbial population in the rhizosphere may be due to unadapted microorganisms to their new environment. However, root exudations play a critical role in microbial growth. Besides, biotic and abiotic factors can also affect the functional variety of microbial populations (Strigul and Kravchenko 2006). Microbial inoculation can be carried out with a single isolate or microbial consortia (e.g., co-inoculation). It was found that co-inoculation improves the efficiency of inoculation and plant development (Lopes et al. 2021). Different methods including seed, soil, root, and foliar inoculation are used to inoculate plants with PBM (Fig. 1; Table 1).

Table 1. Effects of different methods of PBM inoculation on plant growth

PBM	Plant
Burkholderia phytofirmans	*Ryegrass*
Pseudomonas sp.	*Cicer areietinum*
Rhizobia	*Oryza sativa*
Streptomyces, Aspergillus, Bacillus	*Triticum* sp.
Pseudomonas aeruginosa, Bacillus amyloliquefaciens, and Trichoderma harzianum	*Oryza sativa*
Pseudomonas fluorescens	*Arabidopsis thaliana*
Pseudomonas putida	*Zea mays*
Bacillus megaterium, Trichoderma longibrachiatum and *Trichoderma simmonsii*	*Glycine max*
Providencia rettgeri, Advenella incenata , Acinetobacter calcoaceticus, and *Serratia plymuthica*	*Avena sativa, Medicago sa*
Bacillus subtili	*Triticum aestivum*



Fi g.1. Methods of inoculation of PBM in host plan

The seed inoculation technique is the most applied method (Simon et al. 2011). Advantages and disadvantages of each inoculation method depend on the tool accessibility, inoculum and seed type (e.g., size, shape, and fragility), the presence of inhibitory components in the seed (e.g., fungicides, micronutrients, and PBM), and costs (Table 2).

Table 2. Methods of PBM inoculation

Method	**Technique**	**Advantage**
Soil inoculation	Granular/powder; liquid inoculation; immobilized microbial cells	Prevents damage to seeds and cotyle
Root inoculation	Foliar spray; root dipping	Microbial inoculation of seeds in high
Seed inoculation	Seed bio-priming and Seed coating	Cost-effective, accurate and useful fo

Soil inoculation

The method of soil inoculation is the direct transmission of PBM to the soil via drenching, soil incorporation, and microcapsules (Romeiro 2007). Inoculation of*Brachiaria brizantha* seeds by *Burkholderia pyrrocinia* and*Pseudomonas fluorescent* was not successful, in contrast, the soil inoculation with drenching improved plant growth and seedlings emergence (Lopes et al. 2021). Soil inoculation with *Pseudomonas* sp. resulted in better nodulation and growth than seed inoculation of *Cicer arietinum*(Bhattacharjya and Chandra 2013). Recently, it has been found that soil inoculation with PGPB improved the growth, the productivity of nutrient and water uptaking by roots of*Ranunculus asiaticus* (Domenico 2020). It has been shown that direct soil inoculation with PGPB and AMF boosts growth, yield, and nutrient uptake (Saia et al. 2015). Soil inoculation with *Pseudomonas aeruginosa* , *Corynebacterium agropyri* , and*Enterobacter gergoviae* was more significant on the disease suppression of aerobic rice compared to *Bacillus amyloliquefaciens* , *Trichoderma harzianum* and *Trichoderma virens* (Ng et al. 2016). A study suggested that nutrient availability increased after soil inoculation of*Providencia rettgeri, Acinetobacter calcoaceticus* and*Serratia plymuthica* (Li et al. 2020). Soil inoculation using *Bacillus subtilis* has been reported to decrease the toxicity of chromium in *Triticum aestivum* (Seleiman et al. 2020).

Root inoculation

In this method, the roots immerse in a microbial solution (Romeiro 2007). After microbial inoculation, the seedlings are grown at a proper substratum for their development. In this way, this method provides plant size standardization and also causes the direct relationship between roots and inoculants to improve root colonization (Ahemad and Kibret 2014). The inoculation of *Burkholderia phytofirmans* with *Vitis vinifera*roots plant's low-temperature tolerance, altered carbohydrate metabolism, and improved plant growth and yield (Fernandez et al. 2012). Root inoculation of *Oryza sativa* with *Rhizobia* was more efficient in improving plant length compared with seed inoculation (Ullah et al. 2017). One study found that root inoculation with *Pseudomonas fluorescens* caused an increase in induced systemic resistance in leaves of *Arabidopsis thaliana*

(Löser et al. 2021). The inoculation of *Pseudomonas putida* with roots of *Z. mays*caused the reduction of leaf necrosis (Planchamp et al. 2015).

Seed inoculation

To decrease the use of chemical seed treatment, the method of seed inoculation with PBM is a better alternative. In this method, seeds immerse in the microbial solution of known concentration. During the germination process, the seed releases carbohydrates and amino acids in the exudates. In turn, microorganisms use the released seed exudates as the nutritional source in soils and then colonize plant roots (Ammor et al. 2008). It has been reported that the inoculation of *Burkholderia phytofirmans* with*Ryegrass* seeds enhanced plant growth, hydrocarbon degradation, and phytoremediation (Afzal et al. 2013). Association of PBM with plant roots caused the modulated phytohormones levels. Compared with seedling inoculation, seed inoculation with PGPB and AMF has been more effective, stimulating the growth and wood production of *Schizolobium parahyba* var. *amazonicum*(Cely et al. 2016). While the growing root tips have not been activated, inoculum stays dormant in the soil (Lopes et al. 2018). In a study, inoculation of wheat seeds of *Streptomyces* , *Aspergillus, Bacillus* with seeds of *T. aestivum* caused the increased grain yield (Barnett et al. 2019). Under cold stress, the inoculation of *Glycine max* seeds with *Bacillus megaterium, Trichoderma longibrachiatum* and *Trichoderma simmonsii* was more efficient in increasing germination indices and seedling growth (Bakhshandeh et al. 2020).

Mechanisms PBM to survive in diverse conditions

Microorganisms can induce several mechanisms to cope with stressful conditions and improve the growth of host plants. Some microbes survive under low and high temperatures, drought, salinity, acid and alkaline conditions (Lopes et al. 2021) through modification of cell walls, metabolic responses, and gene expression (Sharma et al. 2012). Some microorganisms (e.g., *Bacillus* sp., *Azospirillum* sp., and*Pseudomonas* sp.) can secrete volatile organic compounds (VOC) (such as alkyl sulfides, indole, and terpenes). The signal interactions between plants and microbes can be achieved through the distribution of VOC in soil pores (Hashem et al. 2019). Microbes can accumulate amino acids and avoid dehydration and death against low soil moisture (Venturi and Keel 2016). AMF increased soil organic carbon and changed the microbial population in the rhizosphere, thus causing the modification of the rhizosphere (Zhang et al. 2019) The pigments produced by *Bacillus* and *Serratia* can clear radiation and stop DNA damage against high light (Zion et al. 2006). Microorganisms such as *Azospirillum* sp.*, Pseudomonas* sp., and*Bacillus* sp. significantly influenced soil micronutrient accessibility through reduction of solubilization, chelation and oxidation, and altered the pH of their surrounding soils (Souza et al. 2015).

Influence of abiotic factors on PBM

The abiotic factors can induce stress in the metabolism of plants and modified the compositions of root exudates. This can affect the microbiome in the rhizosphere and the interactions between plants and microbes. In this way, the benefits of PBM can be declined by abiotic factors (Fig. 2).

Soil

Soil pH is an important factor in influencing the solubility of various metallic ions and the accessibility of nutrients, as well as the physical properties of the soil. One of the problems with agricultural productivity in the world is high or low pH. Soil salinity can limit plant growth and thus crop productivity. Hence, these conditions reduce the nutrient deficiency and yield and cause ion toxification, osmotic and oxidative stress (Dutta and Bora 2019). Salinity stress influences crop production by declining the levels of mineral availability and growth regulators, and persuading ions interceded toxicity, osmotic stress, and ROS production, which conclusively causes the blockage of seed germination, seedling growth, the onset of flowering and fruit (Salwan et al. 2019). The conditions of soil nutrition also influence PBM efficiency. It has been evaluated that inoculation of PBM was more effective on growth in nutrient-poor conditions (Strigul and Kravchenko 2006). Inoculations of *Pseudomonas* sp., *Bacillus* sp., and*Mycobacterium* sp. caused enhanced plant growth in soils with a nutrient deficit (Mathimaran et al. 2021). In addition, heavy metal contamination in soils can inhibit the beneficial effects of inoculants on plant growth and agricultural productivity (Mathimaran et al. 2021). However, *Pseudomonas aeruginosa* , *Alcaligenes feacalis* , and*Bacillus subtilis* can serve as an effective remedial approach to increase plant tolerance against heavy metals (Aka and Babalola 2016). Another research revealed that *Klebsiella variicola* and *Azospirillum* sp. caused the improved growth and tolerance of *Glycin max*(Kim et al. 2017) and *Z. mays*(Czarnes et al. 2020) under flooding stress.

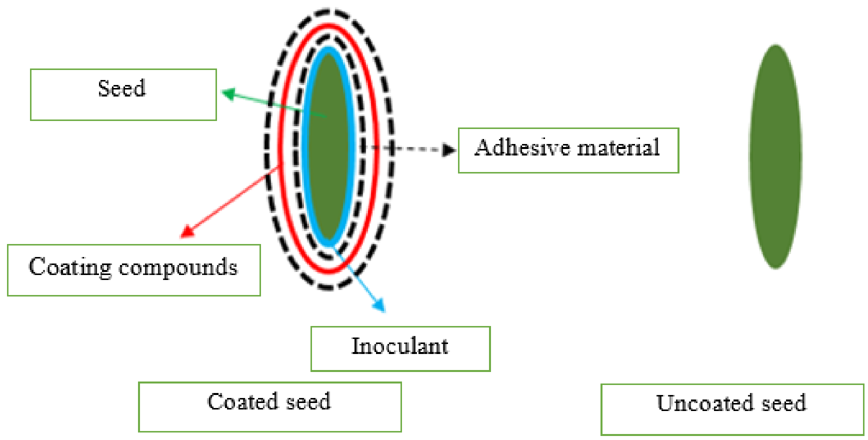


Fig. 2. Schematic of coated seeds (left) and uncoated seeds (right)

Water

PBM such as *Azotobacter chroococcum* and *Azospirillum brasilense* in *Mentha pulegium*(Asghari et al. 2020), *Pseudomonas*sp. and *Azotobacter* sp. in *Cymbopogon citratus*(Mirzaei et al. 2020) can promote plant tolerance against drought stress. Increased soil temperature by water stress can inhibit PBM multiplication. In addition, it has been reported that flooding condition causes the reduction of O_2availability in the soil and restricts the aerobic respiration of microorganisms in soils (Enebe and Babalola 2018). The type of microorganism and light intensity can influence PBM efficiency (Lopes et al. 2018).

Light

Light may alter the interactions between plants and micro-organisms by changing the quantity and chemical compound of root exudates (Lopes et al. 2018). The colonization of microorganisms depends on plant-provided carbohydrates in exchange for nutrients. Under limited light intensity, inoculation of PBM such as*Kaistobacter* sp. and *Pseudomonas* sp. can enhance the growth of *Ophiopogon japonicus* and *Lolium perenne*(Fu et al. 2020). The microbial root symbioses such as *Paraglomus* sp., *Rhizophagus* sp., and*Rhizobium* inhibited the growth of *Phaseolus lunatus*(Ballhorn et al. 2016).

Temperature

Temperature can interfere with interactions between plants and microorganisms by changing root exudation composition, as well as, affecting the morphological, biochemical, and physiological attributes of plants (Meena et al. 2015). Inoculation of PBM such as *Pseudomonas putida* and *Bacillus cereus* can increase the growth of *Triticum* sp. and *Solanum lycopersicum* and decrease the negative effects of high-temperature stress (Ali et al. 2011). Similarly, it has been found that the inoculation of *Burkholderia* sp. increased the tolerance and yield of *Vitis vinifera* under low temperatures (Fernandez et al. 2012).

Microbial seed coating?

Definition of PBM seed coating

In the last years, the application of microorganisms as alternatives to chemical treatments in agricultural products and pastures has increased against various stresses (Deaker et al. 2012). Seed coating is the application of exogenous onto the seed external to boost seed form and handle characteristics such as seed size and weight and delivery of energetic compounds (e.g., plant growth regulators, micronutrients, and microbial inoculants), consequently protecting the seeds from phytopathogens and enhancing germination and plant growth (Pedrini et al. 2017). It is well established from a variety of studies that seed coating with PGPB (such as *Pseudomonas* sp., *Bacillus* sp.), AMF, and *Trichoderma* was an effective and suitable strategy that could introduce PBM into the rhizosphere and provide them to plant roots and other tissues (Rocha et al. 2019b). In comparison to traditional seed treatments, seed coating for different crops was a promising tool that causes a reduced use of inoculum (Afzal et al. 2020). Seed coating with PBM could protect plants against pathogens and improve seed germination against environmental stresses (e.g., drought and salinity) and agrochemicals (e.g., pesticides, growth regulators, and mineral fertilizers) (Ma 2019, Rocha et al. 2019a). Generally, different equipment and methods are used in seed coating to attain good application uniformity and adherence (Jeffs 1986). The use of appropriate seed coating equipment and methods stand can improve plant establishment and seedling vigor under environmental stresses (Ma 2019, Pedrini et al. 2017).

Ingredients of seed coating

The materials used in seed coating include a binder, filler, carriers, and active ingredients (Fig. 2), which assist to release a suitable amount of PBM in physiologic conditions (Ma 2019). Binders are polymers such as the natural and syntactic origin, which ensure the adherence and cohesion of the material on the seed surface and keep the ingredients active (Afzal et al. 2020). The Arabic and xanthan gum can be applied as binders to develop the survival of bacteria, rhizobia, and AMF applied to seeds (Jambhulkar et al. 2016).

The fillers are generally static powders (such as bentonite, calcium carbonate, talc, diatomaceous earth, sand, and wood dust), which can be single or mixed to modify seed shape, size, and weight (Amirkhani et al. 2016, Ma 2019, Pedrini et al. 2017). Nowadays, biochar and chitosan are used as fillers in microbial seed coating (Głodowska et al. 2016). In seed coating, the carriers as one of the factors affecting inoculants should be compatible with these materials and also have the ability to retain sufficient moisture for the growth and survival of inoculants (Jambhulkar et al. 2016). In seeds coated with bio-treatments, some materials such as vermiculite, perlite, etc., are used as carriers, which have high water holding capacity, non-toxicity to seeds, and the capability to stick to the seed external (Ma 2019) and also can assure seedling emergence and quality and the survival of PBM on the seeds (Jambhulkar et al. 2016).

Active ingredients are different from those used in processes of seed coating. The most common active ingredient is protectants, including fungicides, pesticides, insecticides, nematicides, predator deterrents, and herbicides (Yarzábal and Chica 2019), which is used to promote germination and emergence, growth and yield by decreasing predation and putridity by pathogens (Yang et al. 2014). However, sometimes these protectants can negatively affect the germination rate (Qiu et al. 2020). Nutrient amendments, namely macronutrient (e.g., N, P, and K) and micronutrients (Bo, Cu, Mn, Mo, and Zn) applications in seed coating positively affect germination, growth and yield of plants, and also reduce the negative effects of osmotic stress (Pedrini et al. 2017). The most common application of symbiotic microorganisms into coatings involves the inoculation of rhizobia for legumes. The rhizobia-friendly coating formulizations along with the election of desiccation-resistant bacteria modified the survival of symbiotic microorganisms and the beneficial storage life (Scott 1989). To attract and hold water close to the seed, soil hydrophilic materials have been extensively used in seed coating. In addition, the soil surfactant applies within the seed coating materials to enhance water availability to seeds and seedlings in water-repellent soil (Serena et al. 2012).

A range of components (such as PBM, amino acid, chitosan, and soy flour) can be used in the processes of coating seeds of crop and vegetable species in order to stimulate germination and growth, improve stress resistance and establishment, disease reduction, restoration efficacy of native seeds, and protect the finite resource and enhance business for seed technology (Pedrini et al. 2017). The incorporation of fluorescent colorants and magnetic powder into coatings has been expanded to meliorate the traceability of seed batches via the supply chain (Pedrini et al. 2017).

Machines of seed coating

In general, three major kinds of seed coating tools containing a fluidized bed, rotary coater, and rotary pan are used to procreate five kinds of seed coatings, namely dry coating, seed dressing, film coat, entrustment, and seed pellet.

The rotating pan was the first device applied for seed coating, consisting of a circular and usually sloping container rotated by a motor. The seeds were placed in a pan, while the container was spinning, liquids were sprayed on the seeds with a nozzle, and powders were added via a blower or hand spraying (Afzal et al. 2020, Pedrini et al. 2017). The round pan is widely used in the different seed coating methods (Accinelli et al. 2018, Oliveira et al. 2017).

The fluidized or spouted bed apparatus is a cylindrical apparatus that causes the rotation of seeds by airflow through the spray nozzle that atomizes the coating liquid towards the suspended seed mass. This process is used for film coating and surface incrustation, but it is not possible for pelleting.

The rotary coater is an apparatus used in the pelleting and film coating, and it includes a cylindrical drum with a concave disk at the base. Its rotation leads the seed mass to whirl in a regular flow along the drum wall. Usually, a smaller rotating disk attaches to the drum lid and suspends in the middle of the drum. It is accountable for atomising and spraying (Pedrini et al. 2017). In the seed coating industry, these systems are standard in seed treatment. However, nowadays, considering seed coating commercialization and industrial, a lot of information is not disclosed regarding tools and details of seed coating methods.

Types of seed coating

Dry powder coating

Dry powder coating is a method in which seeds are placed in a dry powder and mixed. Also, dry powder can be utilized for bacterial or fungal treatments followed by drying (hydration/dehydration) (Afzal et al. 2020). There is a rotating brush made of stainless steel which sieves a powder material using a dosing sieve (Afzal et al. 2013). It has been reported that talc and graphite are the most common dry powders (Badua et al. 2019). The dosage for dry coating powders used onto seeds is extended with their adherence to seeds and ranges from 0.06 to 1.0% of seed weight (Afzal et al. 2020).

Seed dressing

Seed dressing coating is a method that uses a low dosage of active ingredients to create a thin layer around the seed. In this method, the active materials especially chemical protectants can be used in a wide range (Kimmelshue et al. 2019). The most common equipment in seed dressing is the rotary coater. The rotary coater places the liquids onto a spinning disc and atomizes onto seeds that are spinning inside a metal cylinder, then discharges the freshly treated seeds. The dosage of liquid seed treatment formulations typically ranges from $<$0.05 to 1.0% by weight (Afzal et al. 2020).

Film coating

Film coating is modeled based on the industries of pharmaceutics and confectionary (Afzal et al. 2020) (Fig. 3a). In this method, the seed size does not change, and a small layer (less than 10% of the seed weight) of coating materials such as pigments, fungicides, and polymers are placed around the seed (Ma 2019). During this process, the shape and size of the seed do not change and its application creates successful sowing in the field and protects the environment (Afzal et al. 2020). Nowadays, film coating has been considered an effective and reliable tool to improve crop productivity in the seed industry.

Encrusting

Encrusting is the process of coating seeds by adding liquids and solid particulates to complete seed coverage (Fig. 3b). In this method, the original seed shape is retained, and seedling emergence is improved (Afzal et al. 2020, Pedrini et al. 2017).

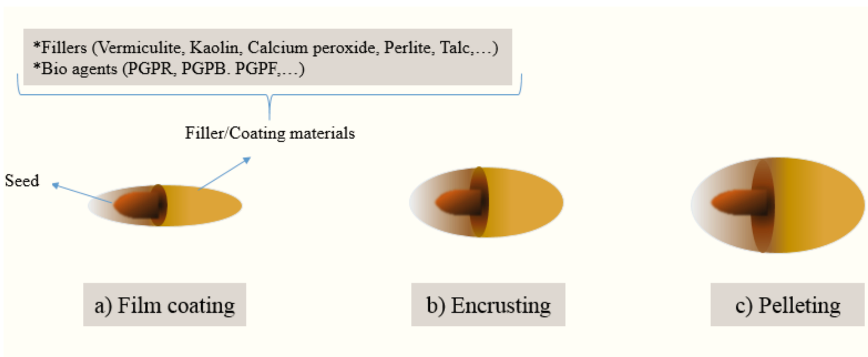


Fig. 3. The three major types of seed coating: film coating (a), entrusting (b) and pelleting (c).

Pelleting

In the seed pelleting process, seeds are coated with inert materials (such as vermiculite, kaolin, calcium peroxide, perlite, talc, and diatomaceous earth) so that the initial size or shape of seeds is not clear (Fig. 3c). Ultimately, seed pelleting cab changes thin seeds into larger and spherical-shaped ones, which could help cultivate very small with low vigor seeds (Afzal et al. 2020, Pedrini et al. 2017).

According to these characteristics of the natural coating of seeds, mainly different agents are used for seed coating, such as protectants, micronutrients (Williams et al. 2016), microorganisms (bacteria and fungi) (Rocha et al. 2019b). The uptake and translocation of agent compounds into seeds can be performed through imbibing seeds in water or emerging radicle and root systems. Overall, the applications of agents are effective in improving seed germination rate, establishment, and increasing the yield of crops (Ma 2019, Pedrini et al. 2017).

Formulation process of seed coating

Three basic components, namely the elected microorganism, an appropriate carrier (solid or liquid), and various additives can be applied to create an efficient formulation of PBM (Rocha et al. 2019a). Various factors such as incorrect formulation of the inoculant and limited shelf life may preclude the application of seed coating (Ahmed and Kumar 2020). The formulation acts a significant role in the inoculation process as it can determine the bioagent potential (Jambhulkar et al. 2016). Nowadays, formulation development by industries is essential to commercialize biocontrol technologies. The expansion of optimal formulations with appropriate carriers for the utilization of microbial inoculants contributes significantly to the control and management of pathogens and seed-borne diseases in crops (Aeron et al. 2011). There are several types of formulations such as wettable powder, liquid, and granular used in soils or spray applications (Knowles 2006).

Shelf life of the microbial coating

An essential commercial issue for seed coating is microbial survival (Bashan et al. 2014). Several factors such as coating type, inoculants (e.g., strain, type, purity, sterile or not, moisture status, and age), coating carrier (e.g., silica, carboxymethyl cellulose, and biochar), drying process (e.g., polymer, final moisture status, time, and temperature), storage condition (e.g., temperature, humidity, water status, polymer, and contaminants) can affect the survival of microorganisms (Ma 2019). It has been reported that the changes in physiology and morphology of cells during inoculants can influence the survival of microorganisms physiological and morphological changes of cells during inoculants can influence the survival of microorganisms (Gemell et al. 2005). In structural biopolymers, water activity and its solvent properties can inhibit the survival of microorganisms during desiccation (Mnasri et al. 2017). Also, at different relative humidity, polymers influence water available to microorganisms by moisture sorption (Deaker et al. 2007). One of the most important factors influencing rhizobia survival on seeds is desiccation (Deaker et al. 2012). During inoculation and inoculated seed storage, the expansion and rate of desiccation depend on the ambient relative humidity. For instance, some studies have reported that relative humidity and water activity are effective in the survival of rhizobia (Mugnier and Jung 1985). Many evidence demonstrated that the survival of microbes is improved when the difference in water status between intracellular and extracellular is reduced (McInnes and Date 2005). Low relative humidity storage of the environment may increase the survival of freeze-dried cells or decrease the survival of completely hydrated survival cells (Kosanke et al. 1992, Ma 2019). For the survival of cells, rehydration is important to improve the cell viability of microbes by decreasing water influx via cell membranes (Deaker et al. 2012, Ma 2019). The polymeric adhesives or coating materials include pigments, nutrients, and protection agents of seeds that can be applied to enhance the survival of microbes on seeds (Deaker et al. 2012, Deaker et al. 2007). Furthermore, polymers can increase the ability to protect cells of microbes against different environmental stresses (Ma 2019). It has been indicated that drying seeds of *Trifolium subterraneum* , *Trifolium repens* , and *Medicago sativa* after coating can enhance microbial survival for a long time (Deaker et al. 2012).

Delivery methods

Innovative seed coating technology can provide the delivery of many kinds of materials that are effective in the enhancement of seedling establishment and plant growth (Jambhulkar et al. 2016). Some studies have shown that several bacteria, including*Pseudomonads fluorescent* , *Pantoea* sp.,*Bacillus cereu,* and the fungus *Trichoderma harzianum*played important role in controlling a range of soil-borne diseases (Moussa et al. 2013). Seed bio-priming is a proceeding of coating seeds with fungal or bacterial agents in which biological and physiological treatments are used to control the disease (El-Mougy and Abdel-Kader 2008). Coating rice seeds with two biological agents *Pseudomonas* and*Bacillus* could protect rice against *Xanthomonas oryzae* and increase seed quality and germination (Palupi et al. 2017). Using*Pseudomonas fluresences* SP700s bacteria as the coating factor not only increased emergence percentage and yield of rice but also reduced dirty panicle disease incidence and severity (Prathuangwong et al. 2013). The*Trichoderma atroviride* inoculated corn seeds had the highest percentage of germination (Gravel et al. 2007). The pathogens of seed-born and soil-born can form a host-parasite relationship through the root. In this regard, PBM can protect the rhizosphere zone against soil-borne diseases. It was demonstrated that the inoculation *Trichoderma harzianum* in soil was more effective in controlling *Armillaria root* rot in*Camellia sinensis* (Mutai 2015). The inoculation of the combinations of *Pseudomonas fluresences*and *Bacillus subtilis* could prevent the growth of pathogens on the wheat roots (Moussa et al. 2013). A study investigated the influence of *Bacillus subtilis* and*Pseudomonas fluorescent* on the germination indices and seedling growth of *Cuminum cyminum* under salinity conditions. Results from this study demonstrated that bacterial inoculation improved the germination and seedling characteristics in both optimal conditions and salinity stress. (Piri et al. 2020). However, the co-inoculation of *Bacillus subtilis* and*Pseudomonas fluorescent* caused a decreasing in plant growth and yield. According to some results of research (Ma et al. 2019), inoculation of single*Rhizophagus irregularis* or dual *Pseudomonas libanensis* +*Rhizophagus irregularis* under greenhouse did not affect cowpea seed yield, however, application of *P. libanensis* increased plant growth performance. Similarly, co-inoculation of *Trichoderma* sp.,*B. bassiana*

, *Metarhizium anisopliae* , and AM fungi had no effect on seed germination of *Lactuca sativa*(Diniz et al. 2006). A reserch showed that coating of *Triticum turgidum* seeds with *P. fluorescens* was more effective on growth parameters than *B. subtilis* and *F. graminearum*(Moussa et al. 2013). A study on the evaluation of biological control of wheat root in field conditions reported that using *P. fluorescents* was the most effective treatment compared to other treatments (Hue et al. 2009).

Application of microbial seed coating in the agricultural system

For billions of years, it has been proved that microorganisms had an intense influence on the whole planet (Akinola and Babalola 2020). Nowadays, the enormous diversity of microbes and their ability on the earth have been known (Pretscher et al. 2018). For instance, bacteria and fungi can manage agricultural sustainability in the world (Akinola and Babalola 2020). It has been confirmed that for developing a sustainable strategy, the application of microbial seed coating in crop production systems can increase crop production, improve resource use efficiency, and protect plants against phytopathogens (Colla et al. 2015).

Enhancement of plant growth and yield

Standardization of size, weight, shape, and uniformity of seeds in seed coating can enhance plantability in the field and crop growth and yield (Ma 2019). While morphological characteristics of the seeds are improved by seed coating, however, seed coating may be an obstacle to germination and emergency (Moussa et al. 2013, Piri et al. 2020). A study has pointed out that delayed germination of *D. carota*(Conceição and Vieira 2008), and *Z. mays* (Nascimento et al. 2009) caused by seed coating is due to coating combinations on imbibition of water and available oxygen. To increase the longevity of coated seeds and microbial functionality *in situ* , the application of an effective formulation plays a role in the expansion of commercial coated seeds (Ma 2019, Rocha et al. 2019a). Application of polymeric adhesives (such as polyvinylpyrrolidone, xanthan gum, methylcellulose) could maintain water activity levels optimal in coating formulations to improve the viability of inoculants (Deaker et al. 2007). To achieve food security and sustainable agriculture, seed quality such as germination, vigor, and mister content is important. Therefore, the microbial seed coating is the seed's primary defense from unfavorable environmental conditions and pathogens, thus improving seed viability and vigor (Palupi et al. 2017). The impact of PBM on plant growth has been reported for numerous crops grown in greenhouse and field environments (Gravel et al. 2007).

Using PBM in seed coating can enhance the percentage of germination, seedling indices, and subsequent plant growth in both optimum and stress conditions (Ma 2019, Rocha et al. 2019a). It has been reported that the yield and macro and microelements, antioxidant activity, total phenolic, caffeoylquinic acids, and flavonoids increased in propagated *Cynara cardunculus* seeds coated by*Rhizophagus intraradices* , *Funneliformis mosseae,* and*Trichoderma atrovirid* (Rouphael and Colla 2020). It has been determined that the use of*Pseudomonas fluorescence bacteria* and *Trichoderma harzianum* in the coating of *C. cyminum* seeds improved seedling emergence rate and seedling growth, antioxidant activity under drought stress in greenhouse conditions (Piri et al. 2019). Similarly, it has been shown that seed coating of *T. turgidum* with *Rhizophagus irregularis* BEG140 using silicon dioxide resulted in an enhancement in shoot dry weight, seed weight and nutrition (K and Zn) contents under low fertilization. Some entomopathogenic fungi associated with plant roots can protect the host plants against disease and insect pests (Oliveira et al. 2016). For instance, the seed coated with entomopathogenic fungi such as *Metarhizium*and *Beauveria* protected *Z. mays* against *Costelytra giveni* and *Fusarium graminearum* and improved germination and growth (Rivas-Franco et al. 2019). Seed coating through the formulation of *T. harzianum, T. viride* and*T. atroviride* enhanced plant growth and germination of *Z. mays* var. saccharata, *T. aestivum* , and *Beta vulgaris*) (Rezaloo et al. 2020).

Alleviation of abiotic stress

The use of PBM as biocontrol agents is an attractive management strategy for both the conventional and organic farming industry that can meliorate plant growth and performance under optimal and stressful conditions and also defend plants across a diversity of soil and seed pathogens (Lazarovits and Subbarao

2010). Besides, several factors have an effective role in the success of microbial seed coating for biocontrol purposes including cultivation practices, dosage, timing, and method of PBM application (Singh et al. 2016). Environmental stresses such as biotic stresses (e.g., drought, salinity, extreme temperatures, and nutrient deficiency, etc.) and abiotic stress (living organisms such as bacteria, viruses, parasitic nematodes, insects, weeds, and other indigenous) are environmental factors that may limit worldwide crop production (Ma 2019, Pedrini et al. 2017). It has been suggested that several PBM (bacterial and fungal strains) such as*Paenibacillus alvei* and *Bacillus amiloliquefaciens* in potato, *Pseudomonas* sp. in potato and strawberry, and *Talaromyces flavus* in tomato were successfully protected plants against *Verticillium dahliae*(Lopisso et al. 2017). The bacteria and fungi application had affirmative agents on plant growth against drought stress and facilitated plant growth and development by supplying mineral nutrients and phytohormones (Aalipour et al. 2020). In a greenhouse, research was found that seed coating of the combination of microbial strains, polymers with several doses of trace and macro-micro-nutrients with *Z. mays* , *G. max* ,*Brassica napus* , *T. turgidum* , *Hordeum vulgare* , and*Lens culinaris* under water-stressed conditions helped to fix plant cell membranes and decreased the damages from drying cycles, and eventually enhanced crop productivity under water stress (Islam and Vujanovic 2017). Seed coating of *Vigna unguiculata* with *Bacillus* sp. could improve the growth and production, and nutrients of crops and decreased usage of the chemical fertilizers in arid agriculture (Nain et al. 2012). The use of a combination of genus *Pseudomonas* , *Azotobacter* ,*Azospirillium* and *Rhizobium* as biofertilizers in coating materials of cotton seed enhanced the growth, relative water content, and contents of chlorophyll and ionic (K^+/Na^+) under both salinity and normal conditions, but decreased shoot growth and leaf gas exchange under salinity stress (Amjad et al. 2015). In an experiment performed under salinity stress conditions, coating maize seeds with *Bacillus* and *Pseudomonas* , and*Pseudomonas* produced more IAA and ACC deaminase, different hydrolytic enzymes, and antifungal activity against two fungal pathogens compared to non-salinity stress (Mukhtar et al. 2020). Co-inoculants of AMF and PGPB onto seeds of soybean in the laboratory and under greenhouse conditions improved the germination, seedling growth, and potassium uptake under drought and salinity stress (Bakhshandeh et al. 2020). In the greenhouse experiment, the growth and photosynthetic state of *T. turgidum* were promoted by seed coating with PGPB *Paraburkholderia phytofrmans* under water-nutrient stress (Ben-Jabeur et al. 2021).

Biological control

Microbial inoculation to soils in the plant ecosystem can help decrease disease damage (Heydari and Pessarakli 2010). The biological potential of *Bacillus thuringiensis* ,*Rhizobium meliloti* , *Aspergillus niger* , and*Trichoderma harzianum* has been evaluated through seed coating with gum arabic, glucose, sugar, and molasses in the suppression of root rot fungi (e.g., *Rhizoctonia solani* and *Fusarium* sp.) on*Helianthus annuus* and *Abelmoschus esculentus* . For instance, seed dressing of microbial antagonists e.g., *B. thuringiensis* , *R. meliloti* and *T. harzianum*improved the microbial efficiency in the control of root rot fungi on crop plants (Meena et al. 2015). Also, it has been reported that the growth parameters such as shoot and root length, shoot and root weight considerably boosted in *A.esculentus* and *H. annuus* plants when seeds were treated with microorganisms, whereas no considerable varieties were perceived in the germination of seed treated by sugar, molasses, glucose, and gum Arabic (Dawar et al. 2008). The research was carried out to appraise the impact of seed coating with biological agents on the seed quality of rice. In this study, isolates of*Pseudomonas and Bacillus subtilis* were tested against*Xanthomonas oryzae* pv. *Oryzae*. Results showed that treatments of biological control boosted seed vigor, and reduced infection of *Xanthomonas oryzae* pv. *Oryzae* in the seed (Palupi and Riyanto 2020). To reduce aflatoxin contamination in corn kernels, the biocontrol techniques were performed via film coating. The findings demonstrated that seeds coated with conventional pesticides such as insecticide (e.g., imidacloprid), fungicide (e.g., metalaxyl-M), and spores of non-aflatoxigenic*Aspergillus flavus* NRRL 30797 reduced aflatoxin contamination of kernels (Accinelli et al. 2018). Lately, it has been found that seed coating and soil drenching with three biocontrol bacterial strains (e.g., strains (e.g., *Providencia vermicola* and *Pseudomonas fluorescens*) boosted cucumber yield and decreased nematode infestation (Panpatte et al. 2021). A biological investigation demonstrated that coating the seeds with the formulation of hydrogel, *Trichoderma harzianum* , and *Burkholderia gladioli* could protect *Phaseolus vulgaris* against common phytopathogens and improve seed germination (Elshafie et al. 2020). Coating seeds of *Triticum durum* with sixty-two rhizosphere and endophytic bacterial strains caused the blockage of growth and germination *Fusarium culmorum* (Mnasri et al. 2017). It has been proved that biological agents used in rice seed coating could improve the seed quality, seedling growth and decrease the blast disease to 0% (Palupi and Riyanto 2020). Seed coating with entomopathogenic fungi *Metarhizium* sp., and *Beauveria* sp. protected seedlings of *Z. mays* against herbivorous insects by enhancing salicylic acid, and jasmonic acid contents (Rivas-Franco et al. 2019).

Ecological restoration by a beneficial microorganism

Restoration of ecology is a process that helps the recovery of degraded, damaged, or destroyed ecosystems. It is well known that PBM and their interactions with plants play an important part in the confirmation of ecological vegetation and sustaining physical structures in soils and nutrient cycling (Chen et al. 2020). Seed coating with PBM can reduce challenges regarding soil moisture variables, low soil nutrients, pathogens in the environment (Gornish et al. 2019). For instance, the inoculation of *Aspergillus* sp. and *Streptomyces* sp. via seed coating improved the emergence of seedlings and survival of *Lolium multiflorum* and *Astragalus sinicus* on degraded rangeland in the Qinghai–Tibetan Plateau (Liu et al. 2010). The use of combination *P. libanensis* and *R. irregularis* in seed coating of cowpea not only enhanced the production of crops but also improved soil fertility and seedlings' tolerance against environmental stresses (Ma 2019). Indeed, the application of PBM can be a suitable tool for the sustainable production of crops and enhancement of yield and ecological restoration under different environmental conditions.

Conclusions and future scenarios

Seed coating is a technique of covering seeds to improve plant establishment and growth, and protect plants against biotic (e.g., pests and diseases) and unfavorable environmental conditions (e.g., drought, salinity, and extreme temperatures), thus providing a secure environment for the next generations. Indeed, the seed coating process is a suitable technology in sustainable agriculture that has received attention today.

Several experimental underlines about microbial seed coating as a biotechnological reach to meliorate crop yield and quality against environmental stress. However, large-scale application and broader use of seed coating have been hindered by several parameters such as survival and viability of microorganisms, selection of the ingredient and accurate formulation, and production cost, which need to be identified by more studies. Also, it is considered that the advantages of microbial seed coating for its application in agriculture are not always assured since it varies with plant species, conditional growth, and experimental scale. However, nowadays using seed coating and efficient PBM strains in agricultural production can provide a commercial market.

The future of seed coating is dependent on formulations, which should be adjusted according to the local conditions and agriculture practices (such as the application of pesticides, fertilizers, and irrigation management). Known PBM formulations obtained by native strains under local conditions need to be further explored. The efficient formulations improve not only the survival of PBM but also the growth and performance of plants. Considering climate changes, the performance of PBM demonstrates in reduction of biotic and abiotic stress. Therefore, the application of PBM in seed coating is promising, and it has great potential for agricultural practice in the future. PBM seed coating is an efficient tool for sustainable agriculture that needs more expansion and investiture to provide its widespread implementation and integration in agricultural management strategies.

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