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Seed coating technology: A sustainable approach for improving seed quality and crop performance

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Abstract

The initial growth phase of agricultural plants, called crop establishment, is crucial and influenced by the quality of the seed used. Seed quality can be affected by various aspects such as genetics and environmental situations, foremost to financial losses for farmers. It is challenging for farmers to control all these factors, but seed coating technology can help by applying physical, chemical, or biological components to the seed surface to enhance its physical properties. Seed coating techniques such as pelleting, encrusting, and film coating increase seed weight and improve crop performance. Seed coating can be a useful means for addressing agricultural challenges and restoring degraded systems, ultimately contributing to improved food security and a more cost-effective ecosystem. This paper provides evidence on different seed coating technologies and discusses their possible benefits.

Keywords: Seed, seed quality, seed coating, seed invigoration, sustainable agriculture

Introduction

Farmers constantly seek high seed quality since it can enhance crop yields by up to 30%. High-quality seeds must be sown, but their use does not ensure effective standard establishment. (FAO, 2014, p. 4) [25]. A wide variety of biotic and abiotic stresses can affect seeds, lowering their expected performance. Yet, careful practice of chemical, biochemical, and biological seed treatments can safeguard and improve development, and prospective yield. (Taylor *et al.* 2020) [71]. With current conventional agricultural practices being unsustainable in addition the impending impact of climate alteration, there is a essential solutions that can improve agricultural productivity while also promoting environmental and economic sustainability (FAO, 2017). Plant helpful microorganisms (PBMs) are being considered as a natural alternative to conventional farming practices to reduce environmental harm. PBMs can assist plants in maintaining or increasing yields though dipping the need for agrochemicals, restoring soil fertility, and addressing issues triggered by biotic and abiotic stresses. Although the use of PBMs has been gaining popularity, conventional agricultural practices such as soil tillage, fertilization, and pesticide application can negatively affect soil microorganisms and their interactions with plants, limiting the effectiveness of PBMs (Ma *et al.* 2019) [53]. Seed inoculation has been identified as an accurate and profitable method for delivering microbial inoculants, where a seed is coated with a carrier, binder, and an active agent such as a microbial inoculant before being planted (Rocha *et al.* 2019) [60].

Seed coating as a technology for enhancement of seed quality was first used for cereal seeds in the late 1930s by “Germains” a British corporation. After that, this technology was commercially accepted and started its application in the late 1960s (Ahmed *et al.*, 2021) [7]. This is one of the components of precision as it encourages quality seed sowing, Uniform size of the seed is maintained when we consider small sized seeds. The coating not only helps in enhancing good germination but also precision seed sowing as seed size is maintained due to uniform coating of every single seed as a result coated seeds are used through seed drill sowing which promotes sowing accuracy. Seed coating can be an effective technique for enhancing seed quality when it includes an active ingredient. This active ingredient can be a physical, chemical, or biological component such as a microbial inoculant that is adhered to the seed coat with the assistance of a binder or filler acting as a carrier. Biological seed treatments are commonly used for pest management and as bio-stimulants, which are natural substances that stimulate physiological and molecular processes that control crop yield and quality. There are various categories of plant bio stimulants, which are ordinary products or biologicals.

This review presents the most recent data on several seed coating techniques and seed coatings, as well as their possible impacts on crop performance.

Seed coating technology

Seed coating is a process of applying a thin layer of protective material to seeds to enhance their germination, growth, and survival. The practice has increased widespread status among farmers and horticulturists due to its ability to improve seed performance and plant establishment. Seed coating has been widely studied and developed over the years, with research focused on improving the effectiveness and efficiency of the process. According to a study by Hafeez *et al*. (2019) [76], seed coating can significantly progress seed quality also plant performance. The researchers found that seed coating with a combination of fungicide and insecticide enhanced seedling emergence, growth, and yield in wheat crops. In one more study by Khan *et al*. (2020) [77], seed coating with plant growth-promoting rhizobacteria (PGPR) improved seed germination, growth, and stress tolerance in maize plants. The researchers concluded that seed coating with PGPR is a cost-effective and eco-friendly method to improve seed and plant performance. Amir *et al*., (2021) [10] concluded from a field experiment that seed coating (on hydroprimed seed) with Bio NPK and drought alleviating bacteria is helpful in improving the planting value of lentil under sub-optimal condition.

Overall, seed coating is an important agricultural practice that has significant potential to progress crop productivity and sustainability. As such, it remains to be an active zone of study and development in the agricultural industry.

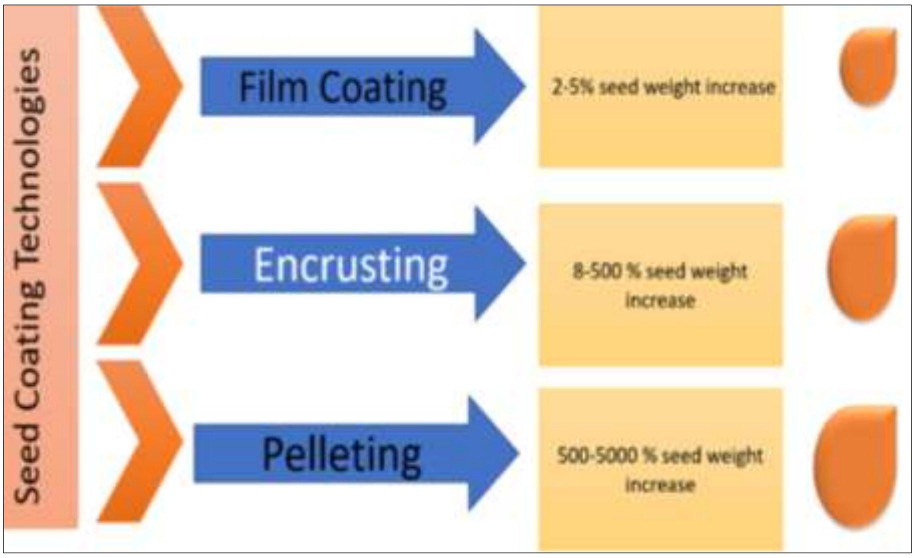

Fig 1: Types of seed coating

Seed film coating

Seed coating is a method that involves adding growth-promoting substances to seeds in order to improve their quality. This is done by applying a thin layer of a beneficial coating substance to the seed coat, which is typically less than 5% of the seed's weight. This approach is highly effective, with over 90% of treated seeds showing improved growth. (Pedrini *et al*., 2017) [78]. By using coating technologies, seeds can be protected from various environmental factors that can harm them, such as biotic and abiotic stresses, from the time of seedling establishment to imbibition (Chandrika *et al*., 2017) [19]. Waterlogging is a main stress that can inhibit plant growth, but coating *Brassica napus* L. seeds with a film containing uniconazole (0.0075%) has been found to significantly alleviate this stress and improve physiological and morphological characteristics. The coating also improved the activity of antioxidant enzymes such as peroxidase, catalase, and superoxide dismutase during waterlogging stress. However, the uniconazole coating did not affect germination under waterlogging stress. Another study found that canola seedlings coated with a polymer film had improved germination when subjected to moisture and low temperature stress. (Willenborg *et al*., 2004) [78]. *Paraburkholderia phytofirmans* rhizobia has been used as a film coating agent to effectively treat wheat plants under drought stress. (Naveed *et al*., 2014) [80]. In a study, it was found that cowpea plants subjected to water scarcity responded positively to microbial inoculation as a film coating (Rocha *et al*., 2019 a, b) [60]. A significant improvement in disease control was observed when comparing coated seeds to untreated seeds. Pigeon pea seeds were coated with zinc and iron nanoparticles (750 ppm), resulting in a remarkable enhancement in seedling appearance, robustness, dehydrogenase, and amylase activities related to raw seeds. (Maity *et al*., 2018) [61].

Seed encrusting

Encrusting is a seed coating process that rises seed weight by 8-100% without significantly altering the seed's shape (Pedrini *et al*., 2017) [78]. The encrusting process involves two important phases: "before coating" (BC) and "coating phase" (CP). In the BC phase, the initial weights of the seed, precipitate, and binder are noted. The CP involves the actual coating process, where small amounts of precipitate and binder are applied to the seed to safeguard good binding (Rocha *et al*. 2019) [60]. Sunflower seeds that were coated with a seed coating material were able to protect the seeds from the harmful effects of herbicides on germination (Piveta *et al*. 2010) [67].

Encrusting fescue seeds before storage bring about in significantly higher germination and vigour compared to untreated seeds and seeds that were encrusted after storage.

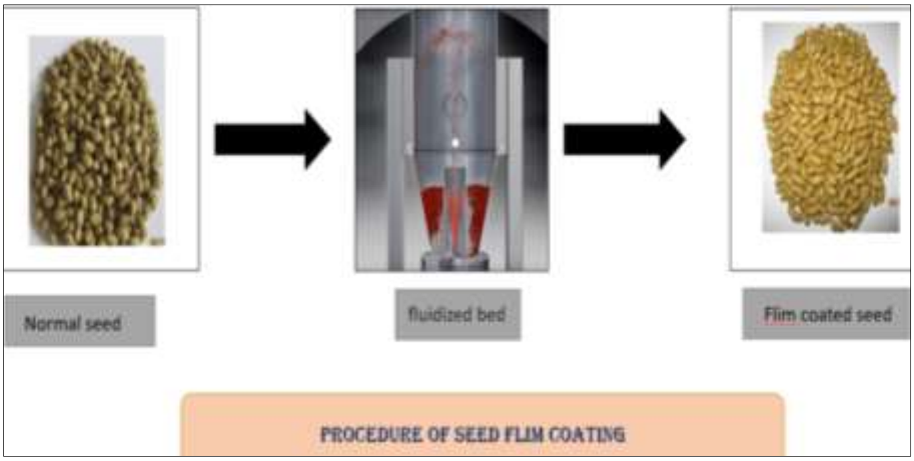

Fig 2: Procedure of seed film coating

Encrusting also had a positive effect on seedling growth and mitigated the negative effects of commercial herbicides. (Olivera *et al*., 2017) [81]. Seed encrusting has been used to successfully deliver rhizobacteria or beneficial plant compounds near the sorption zone. In onion seeds coated with Thiram: Genus's coat, higher levels of germination, vigour index, root length, and shoot length were observed. Seed encrusting has been shown to progress the performance and survival rate of plant growth-endorsing rhizobacteria (PGPR) Zaheer *et al*., 2019) [82]. PGPR-coated seeds have been observed to have higher viability and longer shelf life under varying temperatures and light conditions compared to untreated seeds. (Ma, 2019) [53]. In conclusion, seed encrusting is an effective technique for enhancing seed quality and improving the survival of beneficial microorganisms. It has also been demonstrated that seed encrusting can mitigate the harmful effects of various plant protection agents, particularly during storage.

Seed pelleting

Seed pelleting refers to a technique of adding natural or synthetic materials to seeds in a manner that increases their size, resulting in a uniform shape that makes it difficult to distinguish the original seeds. (Pedrini *et al*., 2017) [78]. Tomato seeds have been successfully improved in relations of vigor, germination, and preservation through the use of seed pelleting. (Javed and Afzal, 2020) [37]. Seed pelleting with a mixture of ammonium molybdate, ferrous sulphate, and rhizobium was found to enhance the growth and yield parameters of soybean (Ramesh and Thirumurugan, 2001) [58]. In another study, seed pelleting was shown to increase the effectiveness of strain *Paenibacillus polymyxa* E681 in biological control of plant diseases, when compared to non-pelleted seeds (Ryu *et al*., 2006) [61]. For tomato seeds, their germination and emergence were improved through pelletization with a mix of talcum, calcium oxide, and bentonite (Javed and Afzal, 2020) [37]. Moreover, research on cowpea seeds demonstrated that seed pelleting led to improved seed quality compared to non-pelleted seeds. These studies highlight the valuable effects of seed pelleting in enhancing various aspects of seed performance and crop growth. Pelletized rice seeds exhibited superior physiological indicators and biochemical characteristics in contrast to non-pelletized rice seeds. (Sun *et al*., 2019) [83].

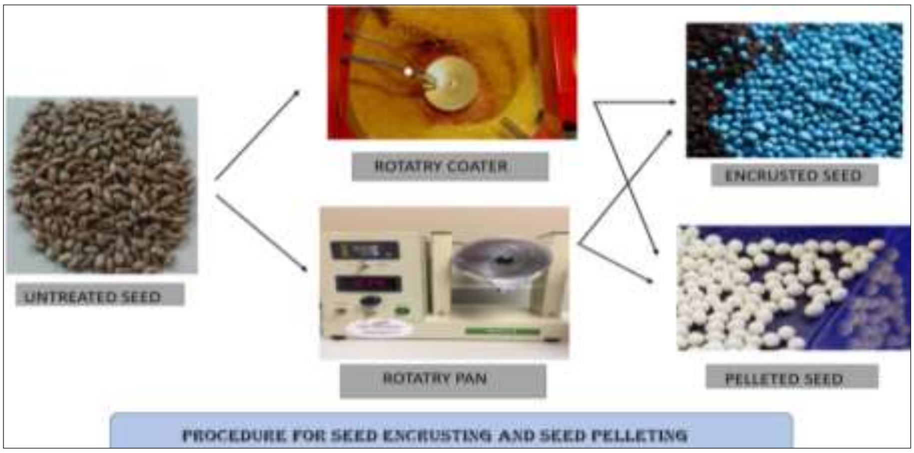

Fig 3: Procedure of seed encrusting and pelleting

Seed coating with plant beneficial microbes (PBM)

Plant beneficial microbes (PBM) play a indispensable role in fostering plant growth and preserving their well-being by establishing a mutualism bond with plants. Coating seeds with PBM is a common and real approach to promoting crop growth, increasing yield, and safeguarding plants from pathogens. Research has demonstrated that seed coating with PBM can lead to improved seedling establishment, enhanced germination, and overall crop productivity and quality, while reducing the reliance on chemical fertilizers. Seed inoculation is an economical method for significant field applications, delivering PBM efficiently (John *et al*., 2010; O'Callaghan,

2016) [84-85]. Compared to other methods like direct soil inoculation, foliar spray, or root dipping, seed inoculation proves to be more efficient, requiring a lower amount of microbial inoculum. By delivering PBM directly to the rhizosphere of the target crop during germination, seed inoculation establishes an intimate plant-microbe contact early on (Philippot *et al*., 2013) [86]. Seed coating with PBM permits for a true application of a small quantity of inoculant at the seed-soil interface, confirming that beneficial microbes are available during the critical stages of germination and early plant development (Scott, 1989) [62]. This, in turn, promotes healthy and speedy plant establishment, ultimately maximizing crop production (Colla *et al*., 2015a) [22]. This review paper focuses on various types of microorganisms known as PBM, which positively impact plant establishment, growth, and development through direct or indirect mechanisms. These microorganisms encompass plant growth-promoting bacteria (PGPB), arbuscular mycorrhizal (AM) fungi, and Trichoderma. Through their symbiotic interactions with plants, these PBM contribute significantly to agricultural sustainability and productivity.

Plant growth-promoting bacteria (PGPB)

In addition to protecting plants against biotic and abiotic challenges, plant growth-promoting bacteria (PGPB) also promote plant growth and performance through both direct and indirect methods (Lugtenberg and Kamilova, 2009The facilitation of nutrient uptake, including nitrogen fixation, phosphorus, and potassium solubilization, are direct impacts of PGPB on plant growth. Along with helpful substances like ammonia, organic acids, and ACC deaminase, PGPB can also create plant hormones including indole-3-acetic acid and cytokinins. (Hayat, 2016) [37] Protecting plants from harm brought on by numerous biotic stressors, such as bacteria, fungi, and nematodes, is one of the indirect impacts of PGPB on plant development and health. These protective effects are achieved primarily through the synthesis of allelochemicals, like antibiotics and hydrogen cyanide, as well as lytic enzymes. Furthermore, PGPB can activate induced systemic resistance, providing additional protection against pathogens (Glick, 2012) [88]. Among the PGPB, rhizobia are commonly employed for nitrogen fixation in pulse crops, contributing to a reduction in the need for chemical fertilizers. Amir *et al*., (2021) [11] reported that seed coating (on hydroprimed seed) with drought alleviating bacteria + BioNPK can be used for higher seed production of lentil under sub optimal conditions. This sustainable practice not only enhances plant growth but also minimizes the reliance on synthetic fertilizers, promoting environmental and agricultural sustainability.

Arbuscular mycorrhiza and Trichoderma

Arbuscular mycorrhiza and Trichoderma are two types of fungi that have long been utilized to enhance nutrient uptake and acquisition in plants. For instance, Arbuscular mycorrhiza can contribute up to 80% of the phosphorus acquired by plants, while plants, in return, transfer about 20% of the fixed carbon to the fungi (Jeffries 2016) [46] It has been demonstrated that using certain Arbuscular mycorrhizal fungi species, including *Glomus intraradices, Rhizophagus irregularis, Funneliformis mosseae* (previously known as Glomus mosseae), and *Rhizophagus fasciculatus,* can significantly increase crop growth and productivity, especially in difficult situations involving salinity and drought stress (Abdul Latef and Chaoxing, 2011) [55] These fungi are crucial in helping plants adapt to external stresses, which ultimately improves agricultural performance and output. When Rhizobium spp. are applied either alone or in conjunction with other plant growth-promoting microorganisms (PBMs), positive benefits in plant growth and production have been seen in several studies. However, due to the possibility of inconsistent results, care must be taken when mixing Rhizobium spp. seed inoculation with other chemical applications. For instance, when infected seeds were treated with lime, the survival of rhizobia was decreased in some species of clover. Similarly, when applied to inoculated seeds, certain fungicides including N-(tri-chloromethylthio)-4-cyclohexene-1,2-dicarboximide, metalaxyl-M, carbathiin, oxycarboxin, and thiram significantly affected the activity of Rhizobium on plant growth and function. These findings highlight the importance of doing in-depth research on the relationship between fungicides and bacterial inoculation agents. This will make it easier to choose suitable fungicides for seed coating treatments that are compatible with the particular Rhizobium strain. By using these measures, the effectiveness of the Rhizobium inoculants will be guaranteed, and successful plant growth will be encouraged.

The presence of significant free-living fungi in the soil and rhizosphere has been linked to metabolites generated during interactions between plants and Trichoderma. Trichoderma treatment can have a considerable effect on a number of plant development factors, including growth, root shape, and nutritional status. It can boost nutrient uptake and solubilization, boost nitrogen usage effectiveness, stimulate systemic resistance, and provide biocontrol against infections while also detoxifying harmful substances in the root zone. Trichoderma has a noticeable impact on plant growth and seed germination when administered alone. (Nawar, 2007;) [64]. Furthermore, it shows efficacy in controlling pthogenic agents like Rhizoctonia solani (Mihuta-Grimm and Rowe, 1986) [62], *Pythium* spp. (Sivan *et al*., 1984; Lifshitz *et al*., 1986; Taylor *et al*., 1998) [68, 69, 72], Sclerotium cepivorum, and Fusarium spp. (Sivan and Chet, 1986; Sivan *et al*., 1987; Babychan and Simon, 2017) [67, 69, 17]. Depending on the specific interactions with other bacterial species when they are coated together, the effects of Trichoderma on plant development and disease incidence can vary. Trichoderma has been seen to have a major effect on plant growth and disease incidence in greenhouse and field settings. However, depending on the exact interaction with the species when coated alongside other bacterial species, the outcome may differ. In a 2016 study, *Trichoderma parareesei*, *Pseudomonas fluorescens*, *Bacillus subtilis*, and *Azotobacter chroococcum* were combined in a talc-based consortium formulation to treat tomato seeds. This treatment significantly reduced the incidence of wilt caused by *Ralstonia solanacearum*. The application of this consortium composition also produced a considerable improvement in fruit output. This research demonstrated the effectiveness of the talc-based seed treatment in promoting disease resistance and enhancing crop productivity in tomatoes. The co-inoculation of Trichoderma spp., *B. bassiana*, *Metarhizium anisopliae*, and AM fungi had a negative effect on lettuce seed growth, significantly reducing it. To gain a better understanding of the impact of seed coating with bacterial species on plant growth and development at every stage of crop development, it is necessary to analyse the interaction and relationship between different species of bacterial inoculants under both laboratory and field conditions.

This statement is a paraphrase of the importance of conducting studies to investigate the effects of different combinations of bacterial inoculants on plant growth and development, as highlighted in various research papers and reviews in the field of plant-microbe interactions.

Nutrient seed coating

Coating the seeds with the essential nutrients including macronutrients and micronutrients enhances the germination as well as do not allow weed growth which is a problem during the field application of major fertilizers. Also, seed coating technique with fertilizers reduces the cost of production. It has been seen that the fertilizer application at early phase of plant growth requires more amount of nutrients rather than later stages depending upon the size of the seed. Larger seeds demand more application than the smaller seeds. Direct application of macronutrients to the seed coat can hamper the germination and subsequent processes therefore before the application of nutrients, it is recommended to coat the seeds with other inert material. The application of slow-release nutrients on the seed results in enhanced performance and increased yield in maize (Dong *et al*., 2016) [25]. Some cereals like rice showed better performance when seed coated with more than one nutrient *viz* mixture of nitrogen, phosphorus and lime leading to well growing and yield. Improved physiological activity has been examined in Barley with seed coating of Phosphorus has been applied (Zeļonka (2005) [94].

Table 1: The effect of different nutrient application for the different crops has been illustrated in the table below.

Source	Application rate	Crop	Main finding	Reference
Boron	1.5 g/kg seed	Chickpea	Seedling growing, grain yield improved also improvement in nodulation.	(Hussain *et al*., 2020) [36]
Fertilizer mastermins	10 mL/100 g seed	Campo Grande *Stylosanthes*	Shoot dry mass improved.	(Baroni and Vieira 2020) [13]
$ZnSO_4$	8.81 g/ kg of seed	Rice	Advanced actions of sulfur-metabolism-enzyme.	(Da-Costa *et al*., 2020) [24]
Calcium peroxide	6 g/ 20g of seed	Rice	Increase in crop establishment.	(Javed *et al*., 2021) [38]
zinc	1.5 g/ kg seed	Wheat	Enhanced seed germination.	(Mohammad and Peksen, 2020) [63]

The low-quality seeds can result into a good germinating seed if treated with optimum amount of nutrients including both macro and micro nutrients at correct dose. The seed coating does not only help with improving germination but also it improves seedling growth (seedling length, seedling DW, shoot length, shoot DW, root length, seedling nutrient). The nutrients applied spreads out to the early root system established by the plant thus improving seedling growth. The percentage of abnormal seedlings can be reduced through nutrient coating. The optimum plant nutrient formulation leads to proper development of emerging coated seeds. This was observed in one of the experiments showing higher germination and speed of seedling emergence when Tomato seeds treated with K_2SO_4 (0.5 mol dm−3), $Ca(NO_3)_2$ (2.5 mol dm−3), KH_2PO_4 (0.05 mol dm−3), $MgSO_4$ (0.3 mol dm−3), KCl (0.05 mol dm−3), FeEDTA (0.05 mol dm−3), H_3BO_3 (0.005 mol dm−3), $MnSO_4.4H_2O$ (2.5 × 10−4 mol dm−3), $CuSO_4 \bullet {}_5H_2O$ (5 × 10−5 mol dm−3), $ZnSO_4.7H_2O$ (1.5 × 10−4 mol dm−3), (NH_4) $6Mo7O_{24}.H_2O$ (2.5 × 10−6 mol dm−3) formulation of nutrients. This nutrient formulation also led to stimulation of total dehydrogenase activity at 48 hours after seed imbibition. Seeds coating with plant nutrient formulation had significantly higher absorption and retention of nutrients in the tomato seedlings at 14 and 30 DAS.

Conclusion

With the main goal of increasing yields through improved establishment, development, and overall crop growth, seed coating technology has shown significant potential for improving seed quality. A crop's ability to grow depends greatly on the quality of its seeds, which are judged by their vigour and potential for emergence. Better stand establishment and seedling vigour can result from the proper application of a suitable seed coating agent in the proper concentration. The difficulties that seedlings face during the development phase, however, cannot be solved with a one-size-fits-all approach, relying on a single or a few modest seed coatings as a universal cure for all limitations in early seedling growth and development. It is necessary to build solid concepts and methodologies for seed coating research as well as a thorough understanding of the complex interactions that are present in seed coatings in order to make meaningful progress in the field. Collaboration amongst experts in a variety of disciplines, including chemical and mechanical engineering, agronomy, soil science, and microbiology, is crucial to achieving this. Such cross-disciplinary cooperation will aid in risk reduction and issue resolution related to seeds, ultimately resulting in higher seed quality. To understand the behaviour and performance of coating agents and to enable the creation of efficient guidelines and processes for seed coatings, it is crucial to have a strong foundation of fundamental knowledge. Additionally, more investigation through transcriptome and proteomic studies is necessary to advance our understanding of the molecular pathways underpinning seed coating-induced seed quality development. Exploring these systems will provide priceless information and boost seed coating technology.

Availability of data and materials

As authors, we will ensure that the availability of data and materials used in the review article on is clearly stated for transparency and reproducibility.

Competing Interests

As a responsible author, I declare that there are no competing interests that may have influenced this manuscript. However, if there are any potential conflicts of interest that were inadvertently omitted, they will be disclosed to the journal immediately.

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