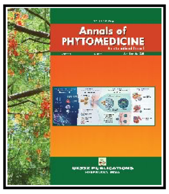
Annals of Phytomedicine 14(2): 177-189, 2025

DOI: http://dx.doi.org/10.54085/ap.2025.14.2.18

Annals of Phytomedicine: An International Journal
http://www.ukaazpublications.com/publications/index.php

Print ISSN : 2278-9839 Online ISSN : 2393-9885



Review Article : Open Access

Maize as a functional crop: Linking seed coating innovations to phytomedicinal and agronomic benefits

K. Pravina*, K. Sujatha*◆, V. Alex Albert*, P. Meenakshisundaram, G. Anand*** and R. Amutha***

**Department of Seed Science and Technology, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai-625104, Tamil Nadu, India*
*** Centre for Innovation, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai-625104, Tamil Nadu, India*
**** ICAR KVK, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai-625104, Tamil Nadu, India*

Article Info

Article history
Received 9 October 2025
Revised 22 November 2025
Accepted 23 November 2025
Published Online 30 December 2025

Keywords
Maize (*Zea mays* L.)
Seed coating
Phytomedicinal potential
Stress tolerance
Sustainable agriculture

Abstract

Maize is a globally important cereal crop with high nutritional, economic and ecological value. It serves as a major food and feed source and supplies raw materials for industries producing biofuels, biodegradable polymers, starch and sweeteners. Although, maize has strong yield potential and grows well in many climates, its cultivation is increasingly challenged by soil degradation, climate variability and attacks from pests and diseases, all of which affect seed vigour and reduce productivity. Seed coating technology has emerged as a sustainable and innovative method to address these challenges by delivering protective, nutritive and bioactive materials directly onto the seed surface. In addition to improving germination and early seedling growth, advanced coatings especially those using natural polymers, biostimulants, micronutrients and nano-enabled materials can also influence the production of important secondary metabolites in maize. These coatings may activate key metabolic pathways (such as PAL, CHS and COMT), enhanced nutrient uptake, regulate plant hormones and improved stress-related signalling, thereby increasing beneficial phytochemicals. This review also highlights major maize bioactive compounds, including phenolic acids (ferulic, p-coumaric, caffeic acids), flavonoids, anthocyanins, carotenoids (lutein, zeaxanthin, β-carotene) and benzoxazinoids (DIMBOA), along with their known antioxidant, anti-inflammatory, antimicrobial and neuroprotective properties. Standard analytical methods such as HPLC/UHPLC-MS/MS, LC-HRMS and GC-MS, as well as common bioassays like DPPH/ABTS/FRAP for antioxidant activity are briefly described for assessing these compounds. By linking seed-coating-induced metabolic changes with phytochemical accumulation and biological activities, this review provides clear insight into how coating technologies can support both crop improvement and health-oriented value addition. The integration of seed coating science with the phytomedicinal potential of maize represents an important step towards sustainable, productive and health-focused agriculture.

1. Introduction

Maize (*Zea mays* L.) often recognized as the "queen of cereals" is one of the world's most important crops due to its exceptional yield potential, adaptability across agro-climatic zones and multiple end uses. A member of the poaceae family, maize provides food security to millions while also serving as a raw material for livestock feed, ethanol, starch, sweeteners and biodegradable polymers, making it indispensable to both agriculture and industry. Its global dominance underscores its dual role in nutrition and economic growth. In India, maize is cultivated in both kharif (monsoon) and rabi (winter) seasons. Nearly three-fourths of the total area is under kharif cultivation, where productivity averages around 2.9 t/ha, while rabi accounts for about one-fifth of the cropped area but achieves higher yields, often exceeding 5.3 t/ha. According to projections from the USDA (2025), maize production in India for 2025-2026 is expected to reach 42 million metric tons, covering approximately 11.5 million hectares with an average national productivity of 3.65 t/ha. Tamil Nadu is a key contributor, accounting for nearly 9% of national maize output and its productivity levels (≈ 3.65 t/ha) are enhanced by favorable growing conditions, extensive use of hybrids and adoption of modern farming technologies.

Maize is a rich source of diverse bioactive compounds distributed across various plant parts including kernels, silk, cob and stover. Among these, phenolic acids such as ferulic acid, p-coumaric acid, caffeic acid, vanillic acid, syringic acid and chlorogenic acid, along with their derivatives, constitute a major class. Ferulic acid is particularly abundant, especially in pigmented maize varieties and is strongly linked with antioxidant activity, providing protection against oxidative stress (Ramírez-Esparza *et al.*, 2024). Flavonoids, including quercetin and rutin, and anthocyanins like cyanidin-3-glucoside are prevalent in colored maize varieties, especially purple and red maize. Anthocyanins are responsible for the vibrant pigmentation and exhibit potent radical scavenging and anti-inflammatory effects (Ramírez-Esparza *et al.*, 2024; Cerino *et al.*, 2020). Carotenoids comprising of lutein, zeaxanthin, β-carotene and β-cryptoxanthin are chiefly found in yellow maize varieties and are known for their antioxidant

Corresponding author: Dr. K. Sujatha
Professor and Head, Department of Seed Science and Technology, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Madurai-625 104, Tamil Nadu, India
E-mail: sujathakseed@tnau.ac.in
Tel.: +91- 9443790200

properties as well as roles in promoting eye health and neuroprotection (Ramirez-Esparza *et al.,* 2024). Additionally, benzoxazinoids such as DIMBOA function as antimicrobial and insect-deterrent compounds, contributing to plant defense mechanisms and holding pharmacological potential (Ramirez-Esparza *et al.,* 2024; Cerino *et al.,* 2020). The pharmacological relevance of these maize bioactives is multifaceted. The antioxidant capacity is primarily credited to phenolic acids, flavonoids, anthocyanins, and carotenoids, which effectively scavenge reactive oxygen species, thus protecting cellular components from oxidative damage (Ramirez-Esparza *et al.,* 2024). Flavonoids including quercetin and rutin exert notable anti-inflammatory effects by inhibiting inflammatory pathways and modulating cytokine production, thereby reducing inflammation (Naeem, 2022; Ramirez-Esparza *et al.,* 2024). Moreover, benzoxazinoids and flavonoids show potential antimicrobial activity against various pathogens and demonstrate neuroprotective effects through anti-apoptotic and anti-inflammatory pathways (Ramirez-Esparza *et al.,* 2024; Hasanudin *et al.,* 2012). Collectively, these bioactive compounds make maize a valuable functional food with promising applications in pharmacology and nutraceutical development.

1.2 Nutritional profile of maize

A 100 g serving of edible maize contains 71.88 g/100 g of carbohydrates, 8.84 g/100 g of protein, 4.57 g/100 g of fat, 2.15 g/100 g of fiber and 10.23 g/100 g of moisture. In addition, maize provides 1.78 mg/100 g of amino acids and 1.5 g/100 g of total minerals. Among the essential minerals present, maize contains 348 mg/100 g of phosphorus, 15.9 mg/100 g of sodium, 114 mg/100 g of sulphur, 10 mg/100 g of calcium, 2.3 mg/100 g of iron, 286 mg/100 g of potassium, 139 mg/100 g of magnesium and 0.14 mg/100 g of copper. It also supplies important vitamins including 0.42 mg/100 g of thiamine, 0.10 mg/100 g of riboflavin and 0.12 mg/100 g of vitamin C (Rouf *et al.,* 2016). Beyond its nutritional profile, maize also possesses notable phytochemical and phytomedicinal properties that enhance its functional value (Rohilla and Singh, 2022). Sweet corn for instance is particularly rich in ferulic acid, a powerful antioxidant predominantly found in its insoluble fractions and cell walls. Remarkably, sweet corn contains the highest known concentration of ferulic acid among fruits and vegetables. This compound plays a protective role against several chronic diseases, including cancer, diabetes, cardiovascular ailments and neurodegenerative conditions such as Alzheimer's disease (Swapna *et al.,* 2020). The vitamins, minerals and bioactive compounds present in maize together contribute to its importance in promoting human health, supporting metabolic functions, enhancing immunity and preventing nutrient-deficiency disorders. Thus, maize stands out not only as an agronomically important crop but also as a nutritionally valuable and medicinally significant food. Different parts of the maize plant such as kernels, silk, husk, and leaves contain a variety of bioactive compounds, including phenolic acids, flavonoids, carotenoids and anthocyanins, which exhibit potent antioxidant, anti-inflammatory and antimicrobial activities (Adom and Liu, 2002; Das and Singh, 2016). These compounds contribute to human health by reducing oxidative stress and supporting metabolic wellness, thus positioning maize not only as a food source but also as a potential nutraceutical crop.

1.3 Relevance of seed quality and need for seed coating technologies in maize

Seed quality plays a pivotal role in maximizing maize productivity. High physiological seed vigor ensures better crop establishment, while improved seed technologies can contribute to a 15-20% increase in yield (Pedrini *et al.,* 2017). However, the interval between harvesting and germination is highly vulnerable as seeds are exposed to biotic and abiotic stresses that can impair their performance (Zaheer *et al.,* 2021). To overcome these challenges, a wide range of physical, chemical, biological and physiological treatments have been developed to maintain seed health and vigor (Sharma *et al.,* 2015). Among these approaches, seed coating has emerged as one of the most promising techniques, as it enables the targeted delivery of protective and growth-enhancing agents directly onto the seed surface. This creates a favorable microenvironment that enhances germination, seedling establishment and stress resilience while offering protection against pathogens and environmental fluctuations (Kaufman, 1991). Recent advances in biopolymer-based and bioactive coatings have also been shown to stimulate the plant's secondary metabolism, leading to improved accumulation of phytochemicals such as phenolics and flavonoids. Thus, seed coating not only enhances productivity and stress tolerance, but may also contribute indirectly to the phytomedicinal potential of maize by improving its biochemical quality. The present review focuses on seed coating technologies suitable for improving maize productivity with particular emphasis on how advanced, eco-friendly coatings incorporating natural polymers, biostimulants and beneficial microbes can strengthen both agronomic performance and phytochemical enrichment. This topic was chosen because integrating seed coating science with the phytomedicinal perspective supports the broader goal of sustainable and functional agriculture, where yield improvement aligns with nutritional and health-promoting benefits. This review provides an overview of conventional coating practices (*e.g.,* clay, fertilizers and protective agents) as well as advanced coating technologies (*e.g.,* polymer, biostimulant, inoculant, micronutrient, herbicide and smart coatings) used in maize with emphasis on their contribution to productivity, resilience and sustainable crop production.

2. Phytochemical extraction, profiling and pharmacological evaluation in maize

The characterization of maize phytochemicals requires strong extraction and analytical workflows that ensure accurate recovery, identification, and quantification of diverse metabolites. Standard extraction protocols commonly employ acidified methanol, ethanol or mixed aqueous organic solvent systems, which effectively solubilize major classes of maize bioactives, particularly phenolic acids and flavonoids. These solvents disrupt cell wall matrices and enhance the release of both free and bound phenolic constituents, thereby improving extraction efficiency. High-performance liquid chromatography (HPLC) and ultra-high-performance liquid chromatography (UHPLC) coupled with tandem mass spectrometry (MS/MS) remain the most widely used techniques due to their superior sensitivity, resolution and structural elucidation capabilities. These systems enable precise quantification of targeted metabolites and facilitate comprehensive profiling even within complex extract matrices (Fougere *et al.,* 2023). For the characterization of volatile compounds particularly those contributing to aroma, defense signalling or secondary metabolism gas chromatography mass spectrometry (GCMS) provides excellent separation and detection efficiency. In parallel, liquid chromatography high-resolution mass spectrometry (LCHRMS) plays an increasingly important role in untargeted metabolomics. LCHRMS platforms support high-throughput detection of known and novel metabolites and function synergistically with molecular networking and advanced data-processing pipelines to elucidate structural diversity within maize phytochemical pools (Fougere *et al.,* 2023). Following extraction and profiling the pharmacological potential of maize phytochemicals is typically assessed through standardized *in vitro* bioassays. Antioxidant activity represents one of the most frequently evaluated properties and is commonly provide complementary insights into the antioxidant mechanisms of maize-derived phenolics, flavonoids, carotenoids and anthocyanins (Ijaz *et al.,* 2016). Anti-inflammatory activity is commonly evaluated using nitric oxide (NO) inhibition assays and cytokine quantification in cell-based systems. No production is measured using the Griess reagent, while cytokine levels (*e.g.,* TNF-α, IL-6) are quantified through ELISA. Suppression of no synthesis and pro-inflammatory cytokines reflects the capacity of maize phytochemicals particularly flavonoids, phenolic acids and benzoxazinoids to modulate inflammatory pathways (Baliyan *et al.,* 2022). Collectively, these standardized extraction, analytical, and pharmacological methodologies provide a rigorous framework for investigating the bioactive landscape of maize. They also support the growing interest in maize as a functional crop with nutraceutical and therapeutic potential.

3. Seed coating technique

Seed coating is the process of applying external materials onto the seed surface to improve handling efficiency and deliver bioactive substances that protect seeds from pests and diseases. Beyond serving as a protective barrier, this technology enhances seed germination, vigor and early seedling establishment (Rocha *et al.,* 2019). Over time, seed coating has advanced from simple protective applications to multifunctional systems designed to address diverse agronomic needs. These modern coatings safeguard seeds against insect pests and fungal pathogens, facilitate beneficial symbiotic associations such as rhizobial colonization, supply nutrients directly to the root absorption zone and improve soil moisture retention through materials with high water-holding capacity. Additionally, they can serve as carriers for growth regulators or stimulants, compounds that release oxygen under low-aeration conditions and agents that modify seed size and density to enhance sowing precision (Taylor, 2020). Because seeds encounter numerous biotic and abiotic stresses during germination and early growth, coating technologies play a vital role in mitigating these effects from the imbibition phase to seedling development (Chandrika *et al.,* 2017). Furthermore, seed coating innovations contribute to the phytomedicinal potential of maize by improving nutrient uptake, stimulating antioxidant enzyme activities and promoting the biosynthesis of valuable secondary metabolites such as phenolics, flavonoids and antioxidants. These biochemical enhancements strengthen the plant's metabolic functions and resilience, leading to increased accumulation of bioactive compounds that enhanced both the nutritional and medicinal qualities of maize (Rocha *et al.,* 2019). Seed-coating technologies mechanistically influence secondary metabolite biosynthesis in maize primarily through modulating key biosynthetic pathways, nutrient uptake, reactive oxygen species (ROS) signalling and hormone regulation. Seed coatings that incorporate biostimulants or bioactive polymers have been shown to activate enzymes such as phenylalanine ammonia-lyase (PAL), chalcone synthase (CHS), and caffeic acid O-methyltransferase (COMT), which are crucial in the phenylpropanoid and flavonoid biosynthetic pathways. This leads to enhanced production of secondary metabolites like phenolics and flavonoids, which contribute antioxidant and protective functions (Rouphael *et al.,* 2020). Furthermore, seed coatings improve root system architecture, increasing root density and length, thereby enhancing nutrient uptake of nitrogen, phosphorus and other essential elements. This improved nutrient status fuel metabolic pathways responsible for secondary metabolite synthesis (Rouphael *et al.,* 2020). ROS-mediated signalling also plays a critical role; seed coatings containing compounds such as hydrogen peroxide or chitosan induce mild oxidative stress that triggers defense responses and secondary metabolite accumulation. This is supported by findings where hydrogen peroxide seed coating increased catalase and peroxidase activities, enhancing antioxidant enzyme systems and promoting phenolic compound synthesis (Lizárraga-Paulín *et al.,* 2013). Additionally, hormonal modulation through seed coating treatments affects secondary metabolism. Alteration in levels of plant hormones such as abscisic acid, gibberellins and brassinosteroids has been reported, which regulate gene expression involved in secondary metabolite biosynthetic pathways (Rouphael *et al.,* 2020).

3.1 Conventional seed coating

Conventional seed coating involves covering the seed surface with external materials to improve physical attributes such as shape, weight, size and surface smoothness. These coatings are generally composed of readily available and inexpensive substances like clays (kaolin, bentonite), talc, lime, peat moss, or crop protection agents. The main purposes of such coatings are to provide mechanical protection during handling, offer chemical defense against pathogens and insect and assist in retaining moisture around the seed. Collectively, these improvements enhance seed flow during sowing, ensure more precise planting and support uniform seedling establishment. Because of their low cost, practically proven effectiveness, conventional coating methods have been integrated into agricultural systems for many years (Pedrini *et al.,* 2017).

3.1.1 Clay based coating

Clay based coatings have become increasingly important in both agriculture and ecological restoration because of their diverse functional advantages. Early studies by Scott (1989) reported that conventional coatings often incorporated clay materials such as bentonite or talc to improve seed handling, enhance flowability and provide mechanical protection during sowing. These properties promote uniform germination and early seedling establishment, provided that coating thickness is carefully optimized to prevent inhibition of seed emergence. Subsequent research expanded on these foundational findings; Madsen *et al.* (2016) demonstrated that clay coatings play a crucial role in maintaining seed-zone moisture and creating a favorable micro site that supports rapid and uniform germination, particularly under stress-prone or arid conditions. Beyond their physical and moisture-retention benefits, clays also serve as efficient carrier materials for fungicides, micronutrients and beneficial microbes (Halmer, 2008; Pedrini *et al.,* 2017). Such combinations provide early protection against pathogens and enhance nutrient bioavailability. Recent advancements have highlighted the potential of nutrient-enriched and bioactive clay coatings in improving maize phytochemical composition and productivity. For example, zinc-enriched clay coatings promote better photosynthetic efficiency and chlorophyll synthesis, resulting in enhanced biomass accumulation and grain yield (Cakmak, 2008). Similarly, coatings incorporating vermiculite, kaolin, or chitosan have been shown to improve soil moisture retention, root vigor and nutrient absorption factors directly linked to improved stress resilience and metabolic activity (Behboud *et al.,* 2024). These favorable physiological conditions stimulate the biosynthesis of phytomedicinally important compounds such as phenolics, flavonoids and antioxidants, which not only strengthen the plant's defense systems but also enhance its overall metabolic efficiency. Enhanced phytochemical production contributes to improved oxidative stress management and membrane stability, resulting in healthier, more vigorous plants capable of sustaining higher productivity under both optimal and adverse growing conditions. Thus, clay-based coatings not only support early seed establishment but also indirectly contribute to yield improvement by enhancing the plant's physiological and phytochemical resilience, leading to better grain filling, nutrient accumulation and overall crop performance (Ismail and Ozawa, 2007).

3.1.2 Fertilizer coating

A growing body of research demonstrates that direct application of plant nutrients through seed coating technologies significantly enhances maize productivity, nutrient-use efficiency and stress resilience (Scott, 1989; Farooq, 2012). Traditional fertilization practices, such as broadcasting are often inefficient due to high nutrient losses through leaching and fixation, which limit nutrient availability during early crop growth stages. In contrast, nutrient-enriched seed coatings offer a more efficient and targeted delivery system, ensuring that essential nutrients are released in proximity to the germinating seed and developing root zone, thereby improving nutrient uptake and utilization efficiency. Recent advances in fertilizer coating formulations have emphasized controlled or slow-release mechanisms, which synchronize nutrient availability with plant demand. Guan *et al.* (2014) demonstrated that attapulgite clay based slow-release coatings significantly improved nutrient use efficiency and grain yield in maize compared to conventional fertilization methods. Similarly, Trenkel (2021) reported that controlled-release and stabilized nutrient coatings enhanced nutrient uptake efficiency while reducing environmental nutrient losses. Complementary findings by Dong *et al.* (2016) revealed that coated and stabilized nitrogen fertilizers (CSUs) minimize nitrogen leaching and volatilization, resulting in improved maize yields, stronger seedling vigor and greater nitrogen-use efficiency than traditional uncoated urea. Beyond yield improvement, nutrient coatings contribute to enhanced stress tolerance and physiological resilience. Matłok *et al.* (2022) observed that maize seeds treated with a nutrient formulation (Dr. Green PRIME) exhibited lower accumulation of reactive oxygen species (ROS) under drought conditions (20% soil water-holding capacity) and higher activity of key antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT) and guaiacol peroxidase (GPOX). These biochemical responses indicated that nutrient coatings not only improves the nutrient efficiency but also stimulate antioxidant defense pathways that mitigate oxidative stress and enhance plant survival under water deficit conditions. Moreover, fertilizer coatings create a localized nutrient-rich microenvironment that accelerates metabolic activation, promoting rapid and uniform germination and vigorous seedling establishment (Tsvigu *et al.,* 2025). Enhanced nutrient uptake further stimulates secondary metabolic pathways associated with the biosynthesis of phenolics, flavonoids and antioxidants compounds that play critical roles in plant defense and contribute to the phytomedicinal and nutritional value of maize (Rocha *et al.,* 2019). Collectively, these findings underscore that nutrient-enriched seed coatings represent a sustainable and efficient strategy to simultaneously enhance maize yield, resilience and phytochemical richness, aligning with the goals of climate-smart and nutritionally enriched agriculture.

3.1.3 Protective coating

Seed coating is a widely adopted strategy for protecting seeds from pathogens originating either internally or from the surrounding soil environment. This protection is typically achieved through the application of fungicidal agents or natural bio-protective substances directly onto the seed surface (Ozer and Coskuntuna, 2016). In maize, these protective coatings have become a cornerstone of integrated pest and disease management, providing early-season defense during the most vulnerable stages of crop establishment. In addition to fungal protection, insecticidal seed coatings have gained increasing importance for controlling early-stage pests such as the fall armyworm (*Spodoptera frugiperda*), a major threat to global maize production. Several chemical combinations have been tested for their efficacy in FAW management. Oliveira *et al.* (2022) demonstrated that seed-applied diamide insecticides as well as mixtures of carbamates and neonicotinoids effectively reduced FAW feeding damage on maize whorls and stalks under suitable environmental and pest susceptibility conditions. Similarly, Li *et al.* (2022) emphasized that combining diamides with neonicotinoids represents a cost-efficient and practical component of integrated pest management (IPM) strategies in maize production systems. In terms of disease suppression, fungicidal seed coatings have shown substantial promise. Degani *et al.* (2018) reported that a combination of azoxystrobin and difenoconazole effectively delayed the onset of late wilt caused by *Harpophora maydis* reducing fungal DNA accumulation in maize tissues and improving cob yield. Chanda *et al.* (2021) further demonstrated that coatings containing cyantraniliprole and thiamethoxam significantly reduced FAW infestations, while Muraro *et al.* (2020) observed only moderate protection with chlorantraniliprole alone or when combined with imidacloprid and thiodicarb. More recent work by Behera and Muralimohan (2024) identified chlorantraniliprole 62.5 FS as highly effective against early and mid instar FAW larvae, while Alam *et al.* (2020) reported that tetraniliprole based treatments provided dual benefits by suppressing *Chilopartellus* infestations and improving grain yield. Multi-component fungicidal coatings have also gained attention for their broad-spectrum efficacy. Capo *et al.* (2020) demonstrated that a four-way mixture containing fludioxonil, metalaxyl-M, azoxystrobin and thiabendazole was more effective in suppressing *fusarium* promoting early seedling growth and enhancing final yield compared with dual-component formulations. A notable commercial development in this category is fortenza duoa systemic seed treatment by syngenta combining cyantraniliprole (a group 28 diamide insecticide) with other protectants. This formulation provides systemic protection by translocating the active ingredient into emerging leaves, thereby reducing reliance on post-emergence foliar sprays (Syngenta, 2014 and 2019). Beyond direct pest and disease control, protective seed coatings also mitigate abiotic stresses such as salinity and drought. By improving nutrient uptake, enhancing antioxidant enzyme activities and regulating endogenous hormone levels (*e.g.,* indole-3-acetic acid, IAA), these treatments strengthen plant physiological functions (Patyal *et al.,* 2025). This enhanced stress tolerance indirectly supports the biosynthesis of phytochemicals such as phenolics, flavonoids and antioxidants compounds that contribute to the phytomedicinal and nutritional value of maize while promoting overall plant vigor and productivity. Collectively, advancements in fungicidal and insecticidal seed coating technologies represent a key step towards sustainable maize production. These innovations not only protect plants from early pest and pathogen pressure but also improve germination, uniform stand establishment and yield potential. Furthermore, by reducing the need for repeated pesticide applications such coatings align with the goals of environmentally responsible and integrated crop protection systems.

3.2 Modern seed coating

The primary goal of modern seed coating technology is to apply active ingredients evenly onto the surface of seeds at precise dosages, thereby improving sowing efficiency and supporting better crop establishment. Beyond acting as a carrier for pesticides the coating system has evolved into a multifunctional delivery platform, capable of incorporating biostimulants, nutrients and plant protectants (Afzal *et al.,* 2020). Recent research trends in this field have focused on the development of eco-friendly and functional coating materials, particularly biodegradable polymers, super-absorbent polymers and nanomaterials. These innovative materials are specifically designed to release nutrients in a controlled manner, enhance soil moisture retention around the seed and offer improved defense against pests and pathogens. Importantly, many of these coatings are engineered to naturally degrade once their role is fulfilled, thereby minimizing environmental footprints. The emergence of such advanced formulations reflects an in-depth understanding of seed physiology and soil-plant interactions aiming to optimize germination processes and promote vigorous early seedling growth across diverse agricultural conditions (Hadas, 2004).

3.2.1 Polymer coating

Polymer coating in seed technology involves coating seeds with a polymer film that can improve germination, protect against pests and diseases, enhance seed flow for uniform and increase moisture retention for drought tolerance. This process involves applying polymers, often along with other substances like fungicides, insecticides, nutrients, colorants, to a seed to improve its physical and biological performance. The result is a more uniform, marketable, and resilient seed that performs better in the field (Vanangamudi *et al.,* 2003). For instance, Sujatha and Ambika (2018) demonstrated that polymer seed treatments incorporating fungicides and biofertilizers improved cereal yield, tillering capacity and pest resistance. Similarly, Vercelheze *et al.* (2019) showed that polymer coated maize seeds containing *Azospirillum brasilense* enhanced nitrogen fixation and root development, thereby improving overall plant performance. Polymer matrices have also been employed as carriers for slow or controlled release fertilizers. Xie *et al.* (2019) reported that polymer coated nitrogen fertilizers reduced volatilization and leaching losses while increasing nutrient use efficiency and yield in maize. Akter *et al.* (2021) further observed that coating NPK fertilizers with biodegradable polymer blends synchronized nutrient release with crop demand, thereby optimizing nutrient uptake. Commercial polymer formulations such as Little’s Polykote Red™ (3 ml/ kg seed) have been shown to maintain high germination rates even during extended storage periods (Taylor *et al.,* 1998). Recent advancements in this field include the development of superabsorbent polymer (SAP) coatings that improve water retention in the rhizosphere. SAP coated maize seeds exhibit superior germination, root shoot growth and drought tolerance due to enhanced water availability and reduced soil moisture fluctuations (Rasovsky *et al.,* 2023). Natural polymer coatings, including colloidal chitin have demonstrated biocontrol activity against pests such as the fall armyworm (*Spodoptera frugiperda*), thus providing an eco-friendly alternative to synthetic insecticides (Moorthy *et al.,* 2024). In addition to agronomic benefits, polymer coatings can enhance maize’s phytomedicinal and nutritional properties by stimulating the biosynthesis of secondary metabolites and coatings incorporating chitosan, hydrogen peroxide or biopolymeric complexes activate antioxidant defense mechanisms such as catalase (CAT), peroxidase (POX) and superoxide dismutase (SOD) activity (Paulin *et al.,* 2013). These physiological responses are associated with increased phenolic and flavonoid accumulation, which contribute to maize’s antioxidant potential and medicinal value. Moreover, polymer matrices have been successfully used for the encapsulation of bacteriophages to suppress seed-borne bacterial infections like *Clavibacter michiganensis*, enhancing seed vigor and health without phytotoxic effects (Kimmelshue *et al.,* 2019) and biodegradable polymer coatings incorporating *Streptomyces philanthi* have also shown potential in mitigating aflatoxin contamination by inhibiting *Aspergillus flavus* and *A. parasiticus* growth (Boukaew *et al.,* 2023) and it minimize nutrient losses, reduce the dependency on chemical fertilizers and pesticides and enhance resilience to abiotic stresses such as drought by integrating physical protection, nutrient management and biological enhancement, polymer coatings align with the goals of climate-resilient and precision agriculture. In conclusion, polymer based seed coatings offer a multifaceted strategy for improving maize productivity, seedling vigor and phytomedicinal quality. While continued optimization of coating formulations and field validation under diverse agro-climatic conditions are required, existing evidence underscores their value as a sustainable, scalable approach to modern crop management.

3.2.2 Inoculant coating

Microbial or inoculants based seed coatings represent an eco-friendly and biologically driven innovation in modern agriculture. By directly applying beneficial microorganisms to seeds, this technique enhances seedling vigor, nutrient uptake, stress tolerance and soil fertility while simultaneously reducing dependence on chemical fertilizers and pesticides. Such coatings provide a microhabitat that promotes microbial survival, uniform colonization and effective delivery of microbial inoculants to the rhizosphere during germination (Singh *et al.,* 2013; Ma *et al.,* 2016). Plant growth promoting bacteria (PGPB), including *Azospirillum*, *Azotobacter*, *Pseudomonas* and *Bacillus* species are the most widely used microbial inoculants in seed coating formulations. These bacteria stimulate root and shoot development through the biosynthesis of phytohormones such as indole-3-acetic acid (IAA), gibberellins, cytokinins and auxins (Singh *et al.,* 2013). They also function as biocontrol agents by producing antibiotic compounds such as azine and oomycin, which suppress soil-borne pathogens and improve plant health (Sudewi *et al.*, 2020). In addition, *Arbuscular mycorrhizal* (AM) fungi including *Rhizophagus irregularis* play a critical role in improving water and nutrient uptake, enhancing stress resistance and supporting soil aggregation and structure (Oliveira *et al.,* 2017). The mechanisms through which microbial inoculants benefit plants are multifaceted, encompassing nitrogen fixation, siderophore production, phosphate and potassium solubilization, ethylene and the induction of systemic resistance (ISR) (Bhattacharyya and Jha, 2012; Nadeem *et al.,* 2014). Through these actions inoculated seeds gain improved resilience against biotic and abiotic stresses leading to stronger seedling establishment and enhanced crop yield. Depending on the microbial species and mode of action, inoculants can serve as biofertilizers, biostimulants, stress alleviators or biopesticides, thus contributing to the sustainability of agricultural systems (Ma *et al.,* 2016). A growing body of evidence supports the effectiveness of microbial seed coatings in maize. *Azospirillum brasiliense* inoculation has been shown to significantly increased maize grain yield and biomass (Oliveira *et al.,* 2018). Similarly, plant growth promoting rhizo bacteria (PGPR) consortia applied as seed coatings have produced yield gains of 24-34% in field trials (Breedt *et al.,* 2017). Fungal inoculants such as *Beauveria bassiana* and *Metarhizium* is an entomopathogenic fungus have demonstrated biocontrol potential against the fall armyworm (*Spodoptera frugiperda*) reducing larval development and survival rates (Sari *et al.,* 2023). Moreover, *Metarhizium* microsclerotia, when used as seed coatings, have shown dual functionality as both biostimulants and pest deterrents, mitigating crop damage under field conditions (Lira *et al.,* 2020). Other beneficial microbial formulations include *Trichoderma harzianum*, which enhances root and shoot elongation and seedling vigor (Accinelli *et al.,* 2016) and *Pseudomonas fluorescens*, which improves maize growth and nutrient uptake even under reduced nitrogen fertilizer inputs (Sandini *et al.,* 2019). Seed coatings containing entomopathogenic fungi have further shown the capacity to colonize roots and protect plants from pests such as *Cerotoma givenei* and fungal pathogens like *Fusarium graminearum*, maintaining plant health and growth (Franco *et al.,* 2019). Integration of microbial inoculants with reduced fertilizer rates has demonstrated synergistic benefits, improving maize growth, grain yield and nutrient use efficiency across diverse environments (Adoko *et al.,* 2022). Rocha *et al.* (2019) emphasized that microbial seed coating particularly those incorporating *Rhizophagus irregularis* and PGPB are highly effective delivery systems for beneficial symbionts. These coatings improved the seedling establishment and stress resilience conferred by these microbial symbioses ultimately enhance the accumulation of phytochemicals such as phenolics, flavonoids and antioxidants thus strengthening the phytomedicinal and nutritional profile of maize. In conclusion, microbial inoculants based seed coatings represent a sustainable and biologically intensive approach for improving maize productivity and quality. By integrating plant microbes interactions into seed technology, these coatings promote early vigor, reduce chemical dependency and enhance the phytochemical richness of maize. Continued research on microbial consortia, coating carriers and formulation stability under field conditions will further advance their potential for climate-smart and resilient maize cultivation systems.

3.2.3 Biostimulant coating

Biostimulant seed coatings represent a promising agronomic innovation designed to enhance germination, early seedling development, stress resilience and overall crop productivity. Unlike conventional seed treatments that primarily provide protection against pathogens and pests, biostimulants function through physiological and metabolic activation, improving nutrient efficiency and plant tolerance to abiotic stresses such as salinity, drought and temperature extremes (Rouphael and Colla, 2020; Senthil Kumar *et al.,* 2024; Elamparithi *et al.,* 2025). Although, biostimulants encompass a wide range of natural and synthetic substances, they share two defining features: they are largely derived from biological sources and they enhance plant growth and resilience without adverse environmental impacts (Jardin, 2015). Their efficacy is determined by multiple interacting factor product composition, crop species, soil characteristics and environmental conditions but their overall effects are consistently associated with improved vigor, yield and stress mitigation (Tarantino *et al.,* 2018). According to the widely accepted classification proposed by Kauffman *et al.* (2007), biostimulants fall into three main categories: humic substances (HS), hormone-containing products (HCP) and amino acid-containing products (AACP). Among these, hormone containing products, particularly those derived from seaweed extracts have gained significant prominence due to their rich composition of phytohormones such as auxins, cytokinins and gibberellins. Seaweed extracts are also abundant in vitamins, polysaccharides and trace elements that collectively enhance germination, root initiation and seedling establishment key determinants of high-yielding and sustainable maize production systems (Ali *et al.,* 2021). Experimental studies provide substantial evidence supporting the benefits of biostimulant based coatings. Biostimulant coated maize seeds exhibited increased salinity tolerance, reflected in greater shoot length, fresh biomass, chlorophyll and carotenoid content and reduced sodium accumulation. This improvement was accompanied by lower hydrogen peroxide (H_2O_2) and malondialdehyde (MDA) levels, indicating reduced oxidative stress and membrane lipid peroxidation (Amato *et al.,* 2021) and among natural sources, seaweed derived formulations have received particular attention due to their multifaceted roles as growth promoters, osmoprotectants and natural defense activators. Methanol extracts of *Sargassum* applied at 5 ml/kg maize seeds significantly enhanced physiological and biochemical parameters, improving seed vigor and early seedling growth (Sujatha and Senthil, 2023). Seaweed extracts also possess antifungal and antimicrobial properties, acting as natural bioprotectants that suppress pathogens such as *Fusarium*, *Alternaria* and *Rhizoctonia*, thereby reducing dependency on synthetic fungicides (Jeevitha *et al.,* 2023; Anbazhagan *et al.,* 2023; Mahalakshmi *et al.,* 2024). Mechanistically, biostimulants act by modulating hormonal and antioxidant pathways within the plant. They enhance auxin and cytokinin signaling, thereby accelerating cell division and root initiation. In addition, they strengthen the antioxidant defense system by upregulating the activities of enzymes such as superoxide dismutase (SOD), catalase (CAT) and peroxidases, which detoxify reactive oxygen species (ROS) and protect cells from oxidative injury (Rouphael and Colla, 2020). This biochemical activation promotes improved germination, uniform emergence and sustained physiological performance during early plant growth. Empirical research further supports the efficiency of humic substances and amino acid-based coatings in maize. Seeds coated with humic acid showed improvement in physiological and biochemical traits, leading to higher seed vigor and more consistent early growth performance because of improvement in biochemical attributes (Sivasakthi, 2022). Recently developed seaweed-based formulations such as Ascomax™

and InnoAg™ coatings have been reported to enhance maize growth through the regulation of gene expression associated with stress responses, antioxidant production, and hormonal signaling pathways (Shi *et al.,* 2024). Beyond promoting germination and yield, biostimulant seed coatings play a vital role in improving the phytomedicinal properties of maize by stimulating the biosynthesis of bioactive secondary metabolites. These compounds particularly phenolics, flavonoids, carotenoids, alkaloids and antioxidant enzymes are crucial for both plant defense and human health. Biostimulant induced enhancement of these metabolites results from improved nutrient uptake, hormonal modulation and stress priming, which collectively activate key biosynthetic pathways such as the phenylpropanoid and flavonoid pathways (Campobenedetto *et al.,* 2024). Biostimulant seed coatings not only increase maize productivity but also improve its medicinal and nutritional quality. By activating seed metabolism, they help plants produce more antioxidants and beneficial compounds that protect against stress and support better health value. In summary, biostimulant coatings offer a simple, eco-friendly way to boost maize growth and quality. They help seeds germinate faster, develop stronger roots, absorb more nutrients, and tolerate stress better. As a result, maize plants become healthier, more productive and richer in valuable phytochemicals supporting both sustainable farming and functional food production.

3.2.4 Micronutrient coating

Micronutrient seed coating applies essential trace elements such as Zn, Fe, B, Mn and Mo directly to the seed surface to supply critical nutrients during the earliest stages of seedling development. By delivering nutrients in the seed zone, coatings support enzyme activation, chlorophyll biosynthesis, hormonal balance and stress tolerance while reducing losses from leaching, volatilization or soil fixation; this improves nutrient-use efficiency compared with conventional soil application (Farooq *et al.,* 2012). The effectiveness of these coatings depends on factors such as nutrient identity dose, coating formulation, soil texture and chemistry, moisture regime and seed-to-nutrient ratio (Halmer, 2008). Empirical studies report consistent benefits: Zn-enriched coatings and P-Zn priming improve maize growth in deficient soils (Ahmadi and Salehi, 2024), while coating seeds with a combination of B, Fe, Mn, Mo and Zn has been confirmed as a cost-effective method to enhance maize growth, yield and seed nutritional quality, particularly in nutrient-deficient soils (Ahmadi and Salehi, 2024). Multi-micronutrient blends further enhance seedling biomass, root development, and final grain yield across various soil types (Chen *et al.,* 2023) and modest rates such as 3.6 g $ZnSO_2 \cdot kg^{-1}$ seed have produced measurable yield gains (Shabaz *et al.,* 2015; Mehta *et al.,* 2011). In saline or degraded soils, combining micronutrient coatings with amendments (*e.g.,* biochar) and microbial inoculants can further improve photosynthesis, chlorophyll content, water relations and yield (Hayat *et al.,* 2023). Micronutrient seed treatments also stimulate antioxidant defenses (*e.g.,* SOD, CAT), reduce oxidative damage and promote accumulation of protective phytochemicals including phenolics, flavonoids and proline thereby linking improved nutrition to both stress resilience and enhanced phytomedicinal value (Moradtalab *et al.,* 2018). Overall, micronutrient seed coatings offer a simple, cost-effective and eco-friendly way to improve maize germination, early growth, nutrient use and yield. They also enhance the production of beneficial phytochemicals such as phenolics, flavonoids and antioxidants, which add to the nutritional and medicinal value of maize. With further field testing and improved formulations, this technology can support healthy, high-yielding and sustainable maize production across different farming systems.

3.2.5 Herbicide coating

Herbicide seed coating represents an innovative approach to sustainable weed management particularly for controlling *Striga* a parasitic weed responsible for substantial yield losses in maize. Unlike traditional broadcast or foliar herbicide applications, this technology involves applying herbicides such as imazapyr directly onto the seed surface. This allows for localized, controlled release of the herbicide in the root zone during early seedling development, suppressing weed emergence precisely where it poses the greatest threat and enhancing resource availability for maize seedlings. Consequently, this targeted approach supports better crop establishment, early and yield potential (Lynch, 2004). Field trials across several African countries have demonstrated that imazapyr-coated, resistant (IR) maize seeds can effectively suppress *Striga* throughout the growing season (Kanampiu *et al.,* 2003). Kanampiu *et al.,* (2007) highlighted the distinct advantage of herbicide seed coatings as a low-dose, highly targeted weed control strategy, particularly suitable for smallholder farming systems. This method prevents *Striga* attachment and emergence by acting during the critical window of parasitic root invasion (Kanampiu *et al.,* 2007; Ransom *et al.,* 2012). The adoption of herbicide coated seeds is especially beneficial for resource-limited farmers, reducing herbicide usage, minimizing environmental contamination, and lowering labor demands associated with manual weeding (Kanampiu and Friesen, 2004). For example, Samwel *et al.* (2021) reported that yield increases of up to 60% in herbicide-coated IR maize compared to uncoated seeds and conventional hybrids, achieving effective disruption of *Striga* life cycles with as little as 30 g/ha of imazapyr. Overall, herbicide seed coating offers a promising, efficient and environmentally friendly weed management solution and its integration into maize production systems in *Striga* infested regions has considerable potential to enhance yield stability and support sustainable agriculture. A study by Elbe Hugo (2013) confirmed that the interactions between seed dressings (including fungicides and insecticides) and pre-emergence herbicides on maize emergence and growth and found that treated seeds emerged faster and had higher seedling vigor, which indirectly supports better plant development and capacity for metabolite synthesis due to reduced competition with weeds and pathogens. Although, direct measurement of phytochemical changes was not highlighted, the improved seedling growth and reduced stress provide the physiological basis for enhanced secondary metabolite production.

3.2.6 Smart coatings: Nanotechnology in seed enhancement

Nanotechnology is an emerging field with substantial potential for agricultural applications particularly in seed science. Recent studies indicate that nanoparticles (1 to 100 nm) can significantly improve seed germination and early seedling growth. Pioneering research in the United States demonstrated that nanoparticles enhance germination by promoting water uptake and stimulating cellular metabolism (Khodakovskaya *et al.,* 2009). Beyond germination, nanoparticles can increase nutrient uptake and reduce oxidative stress by decreasing reactive oxygen species (ROS) and enhancing the activity of key antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT) and guaiacol peroxidase (Guha *et al.,* 2022). Various metal oxide nanoparticles have been tested and shown to improve seed vigor across multiple crops (Tamilarasan *et al.,* 2018; Raja *et al.,* 2019), highlighting nanotechnology as a promising tool for precision seed enhancement, even under suboptimal environmental conditions. Shelar *et al.* (2023) reviewed nano materials for seed treatments, emphasizing their potential to enhance germination, improve stress and facilitate targeted agrochemical delivery, while noting the need for attention to environmental safety, regulatory compliance and scalability. Coating maize seeds with Fe_2O_2 nano particles in combination with *Arbuscular mycorrhizal* fungi (AMF) significantly improved yields under drought stress (Fatma *et al.,* 2025). Similarly, seed treatments with ZnO nanoparticles at 25 to 50 mg/g enhanced germination, growth and hormonal activity (Adhikari *et al.,* 2016). In case of field trials, applying ZnO NPs at 20 to 40/ mg/l further improved chlorophyll content, soil enzyme activity, biomass and yield (Tondey *et al.,* 2021). A novel green-synthesized ZnO-CuO hybrid nanoparticle coating demonstrated dual benefits as a growth promoter and antifungal agent, reducing aflatoxin B1 (AFB1) levels while improving germination (Ngwenya *et al.,* 2025). Ezhilarasan *et al.* (2024) reported that coating maize seeds with SiO_2 and TiO_2 nanoparticles (500 to 1000/ mg/ kg) improved both seed quality and crop performance. Among cutting-edge materials, carbon quantum dots (CQDs) ultra-small, fluorescent nanoparticles have shown potential in improving seed germination and root elongation by modulating key physiological and biochemical pathways during early plant development (Maholiya *et al.,* 2023). Maize seeds coated with gelatin-tannic acid carbon dots (GTACDs) exhibited enhanced performance under drought conditions. These coatings absorb soil moisture and gradually release tannic acid-derived carbon dots (TACDs), which upregulate aquaporin (AQP) genes in radicles to enhance water uptake. TACDs also scavenge ROS in roots and are transported to leaves, boosting photosynthesis. Furthermore, GTACDs improve soil biochemical properties, including total carbon (TC), total nitrogen (TN), inorganic carbon (TIC) and organic carbon (TOC), while promoting beneficial rhizosphere microbial communities. Collectively, these effects resulted in higher germination rates, increased root and shoot growth, greater dry biomass and improved photosynthesis and transpiration rates (Ren *et al.,* 2024). Nanoparticles like iron oxide, zinc oxide and chitosan penetrate the seed coat to promote water uptake, induce reactive oxygen species (ROS) signalling and activate antioxidant enzymes (*e.g.,* catalase, superoxide dismutase), which reduce oxidative stress and boost the biosynthesis of beneficial phytochemicals such as phenolics, flavonoids and proline (Mukhtiar *et al.,* 2024). Nanoagrochemicals enable controlled and targeted release of nutrients and protective agents improving nutrient use efficiency and reducing environmental losses compared to conventional treatments, thus supporting metabolic pathways related to phytomedicinal compound synthesis (Shelar *et al.,* 2023). Nanopesticides and nanofertilizers coating in maize provide protective and nutritive effects while minimizing phytotoxicity, thereby promoting healthier plants capable of producing higher quality secondary metabolites important for medicinal uses (Kumari *et al.,* 2023). Seed coatings combining iron oxide nanoparticles and *Arbuscular mycorrhizal* fungi synergistically enhance maize growth, yield and drought tolerance by improving iron nutrition, root symbiosis, antioxidant defenses and soil microbial health. This interaction supports increased phytomedicinal value by promoting plant metabolism and resilience under stress (Fatma *et al.,* 2025). Overall, nanotechnology-based seed coatings offer a transformative approach in maize, providing enhanced germination, improved stress tolerance, better nutrient and water uptake and more sustainable use of agrochemicals. These innovations enable stronger early crop establishment and have the potential to substantially increase yields, contributing to more resilient and efficient maize production systems.

4. Biosafety

Bioactive and nano enabled seed coatings present a powerful advancement in maize production by enabling precise delivery of nutrients, growth regulators and protective agents directly onto the seed surface. Their nano scale features improve adhesion and enable controlled release of active ingredients, enhancing germination, seedling vigour and stress tolerance (Tritean *et al.,* 2024). However, despite these agronomic benefits, such coatings may unintentionally modify the plant's natural metabolite profile, which raises potential concerns for food safety and human consumption (Tritean *et al.,* 2024). Because nanomaterials and biostimulants possess novel physicochemical properties, achieving precise dosage control is critical. Over-application or uncontrolled release may result in phytotoxicity, metabolic imbalances or accumulation of substances beyond safe limits (Javed *et al.,* 2022). Consequently, determining optimal concentrations that maximize performance while ensuring biological safety is essential. To address these concerns, biosafety assessments have become an integral requirement in the development and regulation of nano-enabled coating technologies. These evaluations typically include phytotoxicity tests to determine effects on cell viability, genotoxicity assays to detect potential DNA damage and environmental impact studies to assess risks to soil microorganisms, beneficial fauna and other non-target organisms (Tritean *et al.,* 2024). Such comprehensive, multi-tiered testing ensures that coated seeds do not introduce harmful residues into the food chain and that ecosystem stability is preserved. As scientific innovation progresses, regulatory frameworks worldwide are evolving to incorporate nano safety guidelines. Compliance with these regulations safeguards consumer health, supports environmental stewardship and promotes responsible adoption of advanced seed coating technologies. In summary, while bioactive and nano based coatings offer significant agronomic potential, their safe application requires optimized dosage, rigorous toxicological validation and adherence to regulatory standards.

5. Future perspective

Seed coating technologies in maize cultivation hold immense promise, with innovations geared towards improving resilience, resource efficiency and sustainability. Next-generation smart coatings are being developed to detect environmental cues such as soil moisture, temperature and pathogen presence, thereby regulating nutrient release, moisture retention and stress protection mechanisms. The integration of nanotechnology will further enhance precision and eco-efficiency in delivering nutrients, biostimulants and protective compounds. Biopolymer-based coatings and microbial inoculants will play a central role in fostering beneficial plant–microbe interactions, reducing reliance on synthetic agrochemicals and promoting long-term soil health. Additionally, advancements in precision agriculture, such as AI-driven modelling, drones and remote sensing will allow for real-time monitoring, personalized coating formulations and targeted field application strategies. Future research may also explore seed coatings enriched with bioactive phytochemicals, potentially enhancing the phytomedicinal value of maize and contributing to its functional food applications. As global agriculture shifts toward climate resilience and sustainable intensification, supportive policies, standardized regulatory frameworks and public private innovation partnerships will be essential to accelerate the adoption of environmentally responsible and scientifically validated coating technologies. Together, these advancements position seed coating as a transformative tool for enhancing maize productivity, nutritional quality and ecological sustainability, contributing to long-term food and health security.

6. Conclusion

Seed coating technology plays a vital role in enhancing maize productivity by improving seed performance, germination and crop establishment. Conventional coatings primarily served protective purposes, shielding seeds from pests, pathogens and environmental stress to ensure healthy early growth. In contrast, modern approaches especially polymer-based, bio-based and smart coatings integrate advanced materials and controlled release systems to address specific agronomic needs with greater precision. Smart coatings can sense and respond to environmental cues, enabling regulated nutrient delivery, moisture management and targeted pest and disease control. Moreover, the inclusion of bioactive or biopolymer based components such as chitosan, alginate and seaweed extracts not only enhances stress tolerance but also promotes the biosynthesis of beneficial secondary metabolites, thereby improving the phytochemical and medicinal properties of maize. These innovations contribute to sustainable, resilient and health oriented maize cultivation systems and minimizing environmental impact. Thus, integrating smart and eco-friendly seed coating technologies with an understanding of maize's phytomedicinal potential offers a promising path towards a future ready, sustainable agriculture.

Acknowledgments

Authors are thankful to the staffs of Department of Seed Science and Technology, Agriculture College and Research Institute, Tamil Nadu Agricultural University (TNAU), Madurai, Tamil Nadu for providing support and research facility.

Conflict of interest

The authors declare no conflicts of interest relevant to this article.

References

Accinelli, C.; Abbas, H. K.; Little, N. S.; Kotowicz, J. K.; Mencarelli, M. and Shier, W. T. (2016). A liquid bioplastic formulation for film coating of agronomic seeds. Crop Prot., **89**:123-128. https://doi: org/10.1016/j.cropro.2016.07.010

Achiri, D. T.; Ndode, E. E.; Mbeboh, M. N.; Ngone, M. A.; Ndzeshala, S. D.; Ruppel, S.; Tening, A. S. and Ngosong, C. (2025). Bio-inoculant consortium and organic amendment comprising plant bioactive extract increased maize yield by improving soil nutrient availability and mitigating pest damage. Plant Soil, pp:1-16. dhttps://doi: org/10.1007/s11104-025-07250-8

Adhikari, T.; Kundu, S. and Subba Rao, A. (2016). Zinc delivery to plants through seed coating with nano-zinc oxide particles. J. Plant Nutr., **39**:136-146. https://doi: org/10.1080/01904167.2015.1087562

Adoko, M. Y.; Noumavo, A. D. P.; Agbodjato, N. A.; Amogou, O.; Salami, Ha. A.; Aguegue, R. M.; Ahoyo, N. A.; Adjanohoun, A. and Baba-Moussa, L. (2022). Effect of the application or coating of PGPR-based biostimulant on the growth, yield and nutritional status of maize in Benin. Front. Plant Sci., **13**:1064710. https://doi: org/10.3389/fpls.2022.1064710

Adom, K. K. and Liu, R. H. (2002). Antioxidant activity of grains. J. Agric. Food Chem., **50**(21):6182-6187. https://doi: org/10.1021/jf0205099

Afzal, I.; Javed, T.; Amirkhani, M. and Taylor, A. G. (2020). Modern seed technology: Seed coating delivery systems for enhancing seed and crop performance. Agriculture, **10**:526. https://doi: org/10.3390/agriculture10110526

Afzal, I.; Rehman, H. U.; Naveed, M. and Basra, S. M. A. (2016). Recent advances in seed enhancements. New Challenges in Seed Biology-Basic and Translational Research Driving Seed Technology, In Tech., pp:47-74. dx.doi: org/10.5772/64791.

Ahmadi, M. R. and Salehi, M. (2024). Enhancing maize (*Zea mays* L.) growth and yield through seed priming and micronutrient coating: Effects on agronomic traits and soil nutrient deficiencies. Greenh. Plant Prod. J., **1**:13-27. https://doi: org/10.61186/gppj.1.3.13

Akhter, M.; Shah, G. A.; Niazi, M. B. K.; Mir, S.; Jahan, Z. and Rashid, M. I. (2021). Novel water soluble polymer coatings control NPK release rate, improve soil quality and maize productivity. J. Appl. Polym. Sci., **138**:51239. https://doi: org/10.1002/app.51239

Alam, T.; Prasad, R.; Kumar, S. and Sahoo, S. (2020). Studies on efficacy of tetraniliprole 480 FS on maize crop against maize stem borer *Chilopartellus* (Swinhoe) as seed treatment. J. Exp. Zool. India., **23**:649-652.

Ali, O.; Ramsubhag, A. and Jayaraman, J. (2021). Biostimulant properties of seaweed extracts in plants: Implications towards sustainable crop production. Plants, **10**:53. https://doi: org/10.3390/plants10030531

Ali, S.; Khan, A. R.; Mairaj, G.; Arif, M.; Fida, M. and Bibi, S. (2008). Assessment of different crop nutrient management practices for yield improvement. Aust. J. Crop Sci., **2**:150-157.

Anbazhagan, M.; Kandasamy, S.; Albert, V. A. and Mini, M. L. (2023). Bioefficacy of seaweed coating formulation on seed quality and biochemical attributes in barnyard millet var. MDU 1. Int. J. Clim. Change Environ. Sustain., **11**:45-52.

Baliyan, S.; Mukherjee, R.; Priyadarshini, A.; Vibhuti, A.; Gupta, A.; Pandey, R. P. and Chang, C. M. (2022). Determination of antioxidants by DPPH radical scavenging activity and quantitative phytochemical analysis of *Ficus religiosa*. Molecules (Basel, Switzerland), **27**(4):1326. https://doi:org/10.3390/molecules27041326

Behboud, R.; Moradi, A.; Piri, R.; Dedicova, B.; FazeliNasab, B. and Ghorbanpour, M. (2024). Sweet corn (*Zea mays* L.) seed performance enhanced under drought stress by chitosan and minerals coating. BMC Plant Biol., **24**:991. https://doi: org/10.1186/s12870-024-05704-2

Behera, R. K. and Muralimohan, K. (2024). Seed treatment with diamides provides protection against early and mid-stage larvae of the fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae), in maize. J. Asia-Pac. Entomol., **27**:1102187. https://doi: org/10.1016/j.aspen.2023.102187

Bhattacharyya, P. N. and Jha, D. K. (2012). Plant growth-promoting *rhizo bacteria* (PGPR): Emergence in agriculture. World J. Microbiol. Biotechnol., **28**:1327-1350. https://doi: org/10.1007/s11274-011-0979-9

Boukaew, S.; Mahasawat, P.; Petlamul, W.; Sattayasamitsathit, S.; Surinkaew, S.; Chuprom, J. and Prasertsan, P. (2023). Application of antifungal metabolites from *Streptomyces philanthi* RL-1-178 for maize grain coating formulations and their efficacy as biofungicide during storage. World J. Microbiol. Biotechnol., **39**:157. https://doi.org/10.1007/s11274-023-03604-5

Breedt, G.; Labuschagne, N. and Coutinho, T. A. (2017). Seed treatment with selected plant growth-promoting rhizobacteria increases maize yield in the field. Ann. Appl. Biol., **171**:229-236. doi: https://org/10.1111/aab.12366

Cakmak, I. (2008). Enrichment of cereal grains with zinc: Agronomic or genetic biofortification. Plant Soil., **302**:1-17. https://doi: org/10.1007/s11104-007-9466-3

Campobenedetto, C.; Grange, E.; Mannino, G.; Van Arkel, J.; Beekwilder, J.; Karlova, R.; Garabello, C.; Contartese, V. and Bertea, C. M. (2020). A biostimulant seed treatment improved heat stress tolerance during Cucumber seed germination by acting on the antioxidant system and glyoxylate cycle. Front. Plant Sci., **11:** 836. https://doi: org/10.3389/fpls.2020.00836

Capo, L.; Zappino, A.; Reyneri, A. and Blandino, M. (2020). Role of the fungicide seed dressing in controlling seed-borne *Fusarium* spp. infection and in enhancing the early development and grain yield of maize. Agronomy, **10:**784. https://doi: org/10.3390/agronomy10060784

Chanda, M.; De Groote, H.; Kinoti, L.; Munsaka, A.; Kuntashula, E.; Bruce, A. Y. and Nkonde, C. (2021). Farmer evaluation of pesticide seed-coating to control fall armyworm in maize. Crop Prot., **148**:105691. https://doi: org/10.1016/j.cropro.2021.105691

Chandrika, K. S. V. P.; Singh, A.; Prasad, R. D. and Yadav, P. (2017). Prominence of seed coating for biotic and abiotic stresses. Popular Kheti, **5**:44-46.

Chen, F. B.; Feng, Y. C. and Huo, S. P. (2023). Seed coating with micronutrients improves germination, growth, yield and microelement nutrients of maize (*Zea mays* L.). Biotech. Histochem., **98**:230-242. https://doi.org/10.1080/10520295.2023.2174273

D-Amato, R. and Del Buono, D. (2021). Use of a biostimulant to mitigate salt stress in maize plants. Agronomy, **11**:1755. https://doi.org/10.3390/agronomy11091755

Das, A. K. and Singh, V. (2016). Phytochemical composition and health benefits of maize. Food Rev. Int., **32** (4):460-472.

De Lira, A. C.; Mascarin, G. and Junior, I. D. (2020). Microsclerotia production of *Metarhizium* spp. for dual role as plant biostimulant and control of *Spodoptera frugiperda* through corn seed coating. Fungal Biol., **124**:689-699. https://doi.org/10.1016/j.funbio.2020.03.011

Degani, O.; Dor, S.; Movshowitz, D.; Fraidman, E.; Rabinovitz, O. and Graph, S. (2018). Effective chemical protection against the maize late wilt causal agent, *Harpophora maydis*, in the field. Plos One, **13**:e0208353. https://doi.org/10.1371/journal.pone.0208353

Dong, Y. J.; He, M. R.; Wang, Z. L.; Chen, W. F.; Hou, J.; Qiu, X. K. and Zhang, J. W. (2016). Effects of new coated release fertilizer on the growth of maize. J. Soil Sci. Plant Nutr., **16**:637-649. http://dx.doi.org/10.4067/S0718-95162016005000046

Du Jardin, P. (2015). Plant biostimulants: Definition, concept, main categories and regulation. Sci. Hortic., **196**:3-14. https://doi.org/10.1016/j.scienta.2015.09.021

Elamparithi, R.; Sujatha, K.; Albert, V. A.; Sivakumar, T.; Gurusamy, A. and Mini, M. L. (2025). Synergistic effects of seaweed extract presoaking and foliar spray on the performance of paddy improved Kavuni (CO57). Plant Sci. Today., **12**:1-9. https://doi.org/10.14719/pst.6412

Elbe Hugo, A. (2013). Effects of seed dressings and herbicide interactions on maize seedling emergence and growth. Grain SA Report

Farooq, M.P; Wahid, A. and Siddique, K. H. M. (2012). Micronutrient application through seed treatments: A review. J. Soil Sci. Plant Nutr., **12**:125-142. http://dx.doi.org/10.4067/S0718-95162012000100011

Fatma, W. S.; Ilyas, S.; Budi, S. W. and Widowati, L. R. (2025). Synergistic effects of iron oxide nanoparticles and arbuscular mycorrhizal fungi through seed coating on maize growth and yield under drought stress. J. Ecol. Eng., **26**(9):400-419.

Fougere, L.; Zubrzycki, S.; Elfakir, C. and Destandau, E. (2023). Characterization of corn silk extract using HPLC/HRMS/MS analyses and bioinformatics data processing. Plants (Basel, Switzerland), **12**(4):721. https://doi.org/10.3390/plants12040721

Guan, Y. J.; Wang, J. C.; Hu, J.; Tian, Y. X.; Hu, W. M. and Zhu, S. J. (2013). A novel fluorescent dual-labeling method for anti-counterfeiting pelleted tobacco seeds. Seed Sci. Technol., **41**:158-163. https://doi.org/10.15258/sst.2013.41.1.18

Guha, T.: Mukherjee, A. and Kundu, R. (2022). Nano-scale zero valent iron (nZVI) priming enhances yield, alters mineral distribution and grain nutrient content of *Oryza sativa* L. cv. Gobindobhog: A field study. J. Plant Growth Regul., **41**:710-733. https://doi.org/10.1007/s00344-021-10335-0

Hadas, A. (2004). Seedbed preparation: The soil physical environment of germinating seeds. In: Handbook of Seed Physiology: Applications to Agriculture.

Halmer, P. (2000). Commercial seed treatment technology. In Seed Technology and Its Biological Basis, pp:257-286). Sheffield Academic Press, Sheffield, England.

Halmer, P. (2008). Seed technology and seed enhancement. Acta Hortic., **771**:17-26.

Hasanudin, K.; Hashim, P. and Mustafa, S. (2012). Corn silk (*Stigma maydis*) in healthcare: A phytochemical and pharmacological review. molecules. **17**(8):9697-9715. https://doi.org/10.3390/molecules17089697

Hayat, H. S.; Rehman, A. U.; Farooq, S.; Naveed, M.; Ali, H. M. and Hussain, M. (2023). Boron seed coating combined with seed inoculation with boron tolerant bacteria (*Bacillus* sp. MN-54) and maize stalk biochar improved growth and productivity of maize (*Zea mays* L.) on saline soil. Heliyon, **9**:e22075. https://doi.org/10.1016/j.heliyon.2023.e22075

Ijaz, S.; Ahmad, S.; Khan, A. U.; Hussain, A. I.; Imran, M.; Awan, M. A.; Tahir, M.; Ahmad, I.; Shahid, M. and Sadiq, A. (2016). Antioxidant activity: ABTS, DPPH, FRAP assays. Indian J. Pharm. Sci., **78**(3):257-265.

Ismail, S. M. and Ozawa, K. (2007). Improvement of crop yield, soil moisture distribution and water use efficiency in sandy soils by clay application. Appl. Clay Sci., **37**:81-89. https://doi.org/10.1016/j.clay.2006.12.005

Javed, T.; Afzal, I.; Shabbir, R.; Ikram, K.; Zaheer, M. S.; Faheem, M.; Ali, H. H. and Iqbal, J. (2022). Seed coating technology: An innovative and sustainable approach for improving seed quality and crop performance. J. Saudi Soc. Agric. Sci., **21**(8):536-545. https://doi.org/10.1016/j.jssas.2022.03.003

Jeevitha, P.: Mahalakshmi, P.: Raja, I. Y.: Sujatha, K.: Mini, M. L. and Ayyandurai, M. (2023). Unleashing the antifungal power of seaweeds against *Colletotrichum gloeosporioides* (OCMK-3) in onion production: An *in vitro* study on combatting pathogen growth. Pharma Innov. J., **12**:1241-1248.

Jiang, S., Zhao, S.; Zhao, L.; Zha, Y.; Yu, X.; Yu, B.; Luo, L.; Wu, J. and Yue, E. (2024). Facilitating growth of maize (*Zea mays* L.) by biostimulants: *A* perspective from the interaction between root transcriptome and rhizosphere microbiome. J. Agric. Food Chem., **72**(7). https://doi.org/10.1021/acs.jafc.3c09062

Johnson, S. E.; Lauren, J. G.; Welch, R. M. and Duxbury, J. M. (2005). A comparison of the effects of micronutrient seed priming and soil fertilization on the mineral nutrition of chickpea (*Cicer arietinum*), lentil (*Lens culinaris*), rice (*Oryza sativa*) and wheat (*Triticum aestivum*) in Nepal. Exp. Agric., 41:427-448. https://doi.org/10.1017/S0014479705002851

Kanampiu, F. and Friesen, D. (2004). *Striga* weed control with herbicide coated maize seed. CIMMYT, Nairobi, Kenya.

Kanampiu, F. K.; Kabambe, V.; Massawe, C.; Jasi, L.; Friesen, D.; Ransom, J. K. and Gressel, J. (2003). Multi-site, multi-season field tests demonstrate that herbicide seed-coating herbicide-resistant maize controls *Striga* spp. and increases yields in several African countries. Crop Prot., 22:697-706. https://doi.org/10.1016/S0261-2194(03)00007-3

Kanampiu, F.; Diallo, A. and Karaya, H. (2007). Herbicide-seed coating technology: A unique approach for *Striga* control in maize. Afr. Crop Sci. Conf. Proc., 8:1095-1098.

Kauffman, G. L.; Kneivel, D. P. and Watschke, T. L. (2007). Effects of a biostimulant on the heat tolerance associated with photosynthetic capacity, membrane thermo stability and polyphenol production of perennial ryegrass. Crop Sci., 47:261-267. https://doi.org/10.2135/cropsci2006.03.0171

Khodakovskaya, M.; Dervishi, E.; Mahmood, M.; Xu, Y.; Li, Z.; Watanabe, F. and Biris, A. S. (2009). Carbon nanotubes are able to penetrate plant seed coat and dramatically affect seed germination and plant growth. ACS Nano. 3:3221-3227. https://doi.org/10.1021/nn900887m

Kimmelshue, C.; Goggi, A. S. and Cademartiri, R. (2019). The use of biological seed coatings based on bacteriophages and polymers against *Clavibacter michiganensis* subsp. *nebraskensis* in maize seeds. Sci. Rep., 9:17950. https://doi.org/10.1038/s41598-019-54068-3

Kumari, A.; Rana, V.; Yadav, S. K. and Kumar, V. (2023). Nanotechnology as a powerful tool in plant sciences: Recent developments, challenges and perspectives. Plant Nano Biol., 5:100046, ISSN 2773-1111. https://doi: 10.1016/j.plnan.2023.100046

Li, H.; Feng, L.; Fu, J.; Zhang, Y.; Huang, W.; Duan, T.; Yang, H. and Xing, J. (2022). Seed treatment with diamide and neonicotinoid mixtures for controlling fall armyworm on corn: Toxicity evaluation, effects on plant growth and residuality. Front. Chem., 10:925171. https://doi.org/10.3389/fchem.2022.925171

Liang, L.; Wong, S. C. and Lisak, G. (2023). Effects of plastic-derived carbon dots on germination and growth of pea (*Pisum sativum*) via seed nano-priming. Chemosphere. 316:137868. https://doi.org/10.1016/j.chemosphere.2023.137868

Lizarraga-Paulín, E. G.; Miranda-Castro, S. P.; Moreno-Martinez, E.; Lara-Sagahon, A. V. and Torres-Pacheco, I. (2013). Maize seed coatings and seedling sprayings with chitosan and hydrogen peroxide: their influence on some phenological and biochemical behaviors. J. Zhejiang Univ. Sci. B., 14(2):87-96. https://doi.org/10.1631/jzus.B1200270

Lynch, J. (2004). Agricultural seed having protective coatings. U.S. Patent Application, 10/610,728, US20040077498A1.

Ma, Y.; Oliveira, R. S.; Freitas, H. and Zhang, C. (2016). Biochemical and molecular mechanisms of plant-microbe-metal interactions: Relevance for phytoremediation. Front. Plant Sci., 7:918. https://doi.org/10.3389/fpls.2016.00918

Madsen, M. D.; Davies, K. W.; Boyd, C. S.; Kerby, J. D. and Svejcar, T. J.(2016). Emerging seed enhancement technologies for overcoming barriers to restoration. Restor. Ecol.,24:S77-S84.https://doi.org/10.1111/rec.12332

Magana-Cerino, J. M.; Peniche-Pavía, H. A.; Tiessen, A. and Gurrola-Diaz, C. M. (2020). Pigmented maize (*Zea mays* L.) contains anthocyanins with potential therapeutic action against oxidative stress. Pol. J. Food Nutr. Sci., 70(2):85-99.

Mahalakshmi, P.; Jeevitha, P.; Sujatha, K.; Ayyandurai, M.; Suthin Raj, T. and Karthikeyan, M. (2024). Exploring the antifungal potential of seaweed extract from *Sargassum cristaefolium* for twister blight management in onion. Ann. Phytomed., 13:1-13.

Maholiya, A.; Ranjan, P.; Khan, R.; Murali, S.; Nainwal, R. C.; Chauhan, P. S.; Sathish, J. P.; Chaurasia. and Srivastava, A. K. (2023). An insight into the role of carbon dots in the agriculture system: A review. Environ. Sci.: Nano., 10:959-995.

Mat³ok, N.; Piechowiak, T.; Krolikowski, K. and Balawejder, M. (2022). Mechanism of reduction of drought-induced oxidative stress in maize plants by fertilizer seed coating. Agriculture, 12:662. https://doi.org/10.3390/agriculture12050662

Mehta, P. V.; Ramani, V. P.; Patel, K. P. and Lakum, Y. C. (2011). Compatibility and feasibility evaluation of zinc application with pesticides and bio-fertilizers as seed treatments in maize. Asian J. Soil Sci., 6:42-46.

Montanha, G. S.; Dias, M. A. N.; Correa, C. G. and de Carvalho, H. W. P. (2021). Unfolding the fate and effects of micronutrients supplied to soybean (*Glycine max* (L.) Merrill) and maize (*Zea mays* L.) through seed treatment. J. Soil Sci. Plant Nutr., 21:3194-3202. https://doi.org/10.1007/s42729-021-00598-7

Moorthy, A. V.; Shanthi, M. and Selva Rani, S. (2024). Colloidal chitin synthesised from marine waste as novel eco-friendly antifeedant for the fall army worm *Spodoptera frugiperda* (J.E. Smith). Indian J. Entomol., 86(4):1384.doi:10.55446/IJE.2023.1238

Moradtalab, N.; Weinmann, M.; Walker, F.; Höglinger, B.; Ludewig, U. and Neumann, G. (2018). Silicon improves chilling tolerance during early growth of Maize by effects on micronutrient homeostasis and hormonal Balances. Front. Plant Sci., 9:420. https://doi.org/10.3389/fpls.2018.00420

Mukhtiar, A.; Zia, M. A; Alawadi, H. F.; Naqve, M.; Seleiman, M. F.; Mahmood, A.; Majeed, M. I.; Hafeez, M. B.; Khan, B. A. and Khan, N. (2024). Role of iron oxide nanoparticles in maize (*Zea mays* L.) to enhance salinity stress tolerance. Notulae Botanicae Horti Agrobotanici Cluj-Napoca. 52(3):13695. https://doi.org/10.15835/nbha52313695

Muraro, D. S.; Stacke, R. F.; Cossa, G. E.; Godoy, D. N.; Garlet, C. G.; Valmorbida, L.; O Neal, M. E. and Bernardi, O. (2020). Performance of seed treatments applied on Bt and non-Bt maize against fall armyworm (*Lepidoptera*: *Noctuidae*). Environmental Entomology, 49: 1137-1144. https://doi.org/10.1093/ee/nvaa088

Nadeem, S. M.; Ahmad, M.; Zahir, Z. A.; Javaid, A. and Ashraf, M. (2014). The role of mycorrhizae and plant growth promoting rhizobacteria (PGPR) in improving crop productivity under stressful environments. Biotechnol. Adv., 32:429-448. https://doi.org/10.1016/j.biotechadv.2013.12.005

Naeem, M. (2022). A phytopharmacological review on *Zea mays* Corn silk extract. IJNRD Journal., 7(7):66.

Ngwenya, S. C.; Sithole, N. J.; Mthiyane, D. M.; Jobe, M. C.; Babalola, O. O.; Ayangbenro, A. S.; Mwanza, M.; Onwudiwe, D. C. and Ramachela, K. (2025). Effects of green-synthesised copper oxide-zinc oxide hybrid nanoparticles on antifungal activity and phytotoxicity of aflatoxin B1 in maize (*Zea mays* L.) seed germination. Agronomy, 15:313. https://doi.org/10.3390/agronomy15020313

Oliveira, C.; Orozco Restrepo, S. M.; Alves, A. C. L.; Pinto, B. S.; Miranda, M. S.; Barbosa, M. H. P.; Picanço, M. C. and Pereira, E. J. (2022). Seed treatment for managing fall armyworm as a defoliator and cutworm on maize: Plant protection, residuality, and the insect life history. Pest Manag. Sci., 78:1240-1250. https://doi.org/10.1002/ps.6741

Oliveira, R. S.; Carvalho, P.; Marques, G.; Ferreira, L.; Nunes, M.; Rocha, I.; Ma, Y.; Carvalho, M. F.; Vosátka, M. and Freitas, H. (2017). Increased protein content of chickpea (*Cicer arietinum* L.) inoculated with *arbuscular mycorrhizal* fungi and nitrogen-fixing bacteria under water deficit conditions. J. Sci. Food Agric., 97:4379-4385. https://doi.org/10.1002/jsfa.8201

Ozer, N. and Coºkuntuna, A. (2016). The biological control possibilities of seed-borne fungi. Current Trends in Plant Disease Diagnostics and Management Practices. Fungal Biology. Springer, Cham., 1:383-403. https://doi.org/10.1007/978-3-319-27312-9-17

Patyal, D.; Sachdeva, K.; Sharma, K. and Khan. R. R. (2025). An innovative and sustainable seed coating technology for improving seed quality and crop performance. J. Sci. Res. Rep., 31(5):597-607.

Pedrini, S.; Merritt, D. J.; Stevens, J. and Dixon, K. (2017). Seed coating: Science or marketing spin? Trends Plant Sci., 22:106-116. https://doi.org/10.1016/j.tplants.2016.11.002

Raja, K.; Sowmya, R.; Sudhagar, R.; Satyamoorthy, P.; Govindaraj, K. and Subramanian, K. (2019). Biogenic ZnO and Cu nanoparticles to improve seed germination quality in black gram (*Vigna mungo*). Mater. Lett., 235:164-167. https://doi.org/10.1016/j.matlet.2018.10.038

Ramirez-Esparza, U.; Agustin-Chavez, M. C.; Ochoa-Reyes, E.; Alvarado-Gonzalez, S. M.; Lopez-Martinez, L. X.; Ascacio-Valdes, J. A.; Martinez-Avila, G. C. G.; Prado-Barragan, L. A. and Buenrostro-Figueroa, J. J. (2024). Recent advances in the extraction and characterization of bioactive compounds from Corn by-products. Antioxidants (Basel, Switzerland), 13(9):1142. https://doi.org/10.3390/antiox13091142

Ransom, J.; Kanampiu, F.; Gressel, J.; De Groote, H.; Burnet, M. and Odhiambo, G. (2012). Herbicide applied to imidazolinone resistant-maize seed as a *Striga* control option for small-scale African farmers. Weed Science, 60:283-289. doi:10.1614/WS-D-11-00060.1

Rasovsky, M.; Pacuta, V.; Gazo, J.; Nika, B.; Lenicka, D.; Michalska-Klimczak, B. and Wyszynski, Z. (2023). Impact of seed coating with superabsorbent polymers on morphological, physiological and production traits of maize (*Zea mays* L.). Plant Soil Environ., 69(12):586-595. https://doi.org/10.17221/209/2023-PSE

Ren, Y.; Li, X.; Cheng, B.; Yue, L.; Cao, X.; Wang, C. and Wang, Z. (2024). Carbon dot-embedded hydrogels promote maize germination and growth under drought stress. Environ. Sci.: Nano., 11:2239-2248. https://doi.org/10.1039/D4EN00070F

Rivas-Franco, F.; Hampton, J. G.; Altier, N. A.; Swaminathan, J.; Rostas, M.; Wessman, P.; Saville, D. J.; Jackson, T. A.; Jackson, M. A. and Glare, T. R. (2020). Production of microsclerotia from entomopathogenic fungi and use in maize seed coating as delivery for biocontrol against *Fusarium graminearum*. Front. Sustain. Food Syst., 4:606828. https://doi.org/10.3389/fsufs.2020.606828

Rocha, I.; Ma, Y.; Souza-Alonso, P.; Vosatka, M.; Freitas, H. and Oliveira, R. S. (2019). Seed coating: A tool for delivering beneficial microbes to agricultural crops. Front. Plant Sci., 10: 1357. https://doi.org/10.3389/fpls.2019.01357

Rohilla, B. and Singh, S. P. (2022). A review on the study of nutritional composition and health benefits of sweet corn (*Zea mays L.*) and coconut *(Cocos nucifera)* oil. Ann. Phytomed., 11(2):130-136.http://www.ukaazpublications.com/publications/index.php

Rouf Shah, T.; Prasad, K. and Kumar, P. (2016). Maize: A potential source of human nutrition and health: A review. Cogent Food and Agriculture, 2(1):1166995. https://doi.org/10.1080/23311932.2016.1166995

Rouphael, Y. and Colla, G. (2020). Biostimulants in agriculture. Front. Plant Sci., 11:40. https://doi.org/10.3389/fpls.2020.00040

Rouphael, Y.; Lucini, L.; Miras-Moreno, B.; Colla, G.; Bonini, P. and Cardarelli, M. (2020). Metabolomic responses of maize shoots and roots elicited by combinatorial seed treatments with microbial and non-microbial biostimulants. Front. Microbiol., 11*:664*

Samwel, S. M.; Paul, K. and Joshua, O. (2021). Effectiveness of imazapyr coated hybrids and selected *Striga*-tolerant varieties on *S. hermonthica* management and maize yield performance in western Kenya. Adv. Appl. Physiol., 6:1. doi: 10.11648/j.aap.20210601.11

Sandini, I. E.; Pacentchuk, F.; Hungria, M.; Nogueira, M. A.; da Cruz, S. P.; Nakatani, A. S. and Araujo, R. S. (2019). Seed inoculation with *Pseudomonas fluorescens* promotes growth, yield and reduces nitrogen application in maize. Int. J. Agric. Biol., 22:1369-1375. doi: 10.17957/IJAB/15.1210

Sari, J. M. P.; Herlinda, S. and Suwandi, S. (2022). Endophytic fungi from South Sumatra (Indonesia) in seed-treated corn seedlings affecting development of the fall armyworm, *Spodoptera frugiperda* J. E. Smith (*Lepidoptera*: *Noctuidae*). Egypt. J. Biol. Pest Control., 32:103. https://doi.org/10.1186/s41938-022-00605-8

Scott, J. M. (1989). Seed coatings and treatments and their effects on plant establishment. Adv. Agron., 42:43-83.(08)60523-4. https://doi.org/10.1016/S0065-2113

Senthilkumar, S.; Kuppusamy, S.; Baskar, M.; Vijayalatha, K. R.; Jayavalli, R.; Nithila, S.; Sujatha, K. and Palai, S. (2024). Cultivating tomorrow: A review on biostimulants and their transformative role in agriculture. J. Adv. Biol. Biotechnol., 27:906-919. doi:10.9734/jabb/2024/v27i81211

Shabaz, M. K.; Ali, H.; Sajjad, M.; Malook, S. A. N.; Shah, H. and Ali, Q. (2015). Effect of seed coating with boron and zinc on *Zea mays* for various yield traits. Am.-Eurasian J. Agric. Environ. Sci., 15:1304-1311. doi: 10.5829/idosi.aejaes.2015.15.7.12705

Shelar, A.; Nile, S. H.; Singh, A. V.; Rothenstein, D.; Bill, J.; Xiao, J.; Chaskar, M.; Kai, G. and Patil, R. (2023). Recent advances in nano-enabled seed treatment strategies for sustainable agriculture: Challenges, risk assessment, and future perspectives. Nano-Micro Lett*.,* 15(1):54. https://doi.org/10.1007/s40820-023-01025-5

Siddaraju, R.; Narayanaswamy, S. and Ramanappa, T. M. (2015). A study on the effect of seed coating with synthetic polymer and seed treatment chemicals on physiological changes and seed infestation of maize hybrid Hema (*Zea mays* L.) during seed storage. Seed Technol., pp: 467-477.

Singh, N. K.; Chaudhary, F. K. and Patel, D. B. (2013). Effectiveness of *Azotobacter* bio-inoculant for wheat grown under dryland condition. J. Environ. Biol., 34: 927-932.

Sivasakthi, S. (2022). Development of natural seed coating polymer to improve the planting value of crop seeds (Doctoral Thesis). Tamil Nadu Agricultural University.

Sudewi, S.: Ala, A. and Farid, M. (2020). The isolation and characterization of endophytic bacteria from roots of local rice plant Kamba in Central Sulawesi, Indonesia. Biodiversitas Journal of Biological Diversity, 21. doi: 10.13057/biodiv/d210442

Sujatha, K. and Ambika, S. (2018). Designer seed treatment techniques on enhancement of yield in paddy [E-book]. Indian Council of Agricultural Research (ICAR).

Sujatha, K. and Ramamoorthy, K. (2009). Seed quality enhancement in red gram and greengram by polymer coating. Int. J. Agric. Sci., 5:297-298.

Sujatha, K. and Senthil, K. (2023). Influence of seaweed based seed coating on physiological and biochemical attributes in paddy and maize. Pharma Innovation,12(12):854-859.

Swapna, G.; Jadesha, G. and Mahadevu, P. (2020). Sweet corn: A future healthy human nutrition food. Int. J. Curr. Microbiol. App. Sci., **9**(7):385965.

Syngenta, (2014). *Fortenza Duo* is a next-generation seed treatment insecticide that delivers long-lasting protection, pp:712.

Syngenta, (2019). *Fortenza Duo* (Cyantraniliprole + Thiamethoxam). Syngenta.

Tamilarasan, C.; Raja, K.; Subramanian, K. S. and Selvaraju, P. (2018). Synthesis and development of nano formulation for hastening seed quality in groundnut. Res. J. Agric. Sci., **10**:50-57.

Tarantino, A.; Lops, F.; Disciglio, G. and Lopriore, G. (2018). Effects of plant biostimulants on fruit set, growth, yield and fruit quality attributes of 'Orange Rubis' apricot (*Prunus armeniaca* L.) cultivar in two consecutive years. Sci. Hortic., **239**:26-34. https://doi.org/10.1016/j.scienta.2018.04.055

Taylor, A. G. (2020). Seed storage, germination, quality and enhancements. In H. C. Wien and H. Stutzel (Eds.), Physiol. Veg. Crops., 2nd ed., pp:1-30. CABI Wallingford, U.K.

Taylor, A. G.; Allen, P. S.; Bennett, M. A.; Bradford, K. J.; Burris, J. S. and Misra, M. K. (1998). Seed enhancements. Seed Science Research, **8**:245-256. doi:10.1017/S0960258500004141

Tonapi, V. A.; Babu, P. H.; Ansari, N. A.; Varanavasiappan, S.; Ravinder Reddy, Ch.; Navi, S. and Seetharama, N. (2006). Studies on development of seed coloring standards in paddy and maize. Int. J. Agric. Sci., **19**:278-286.

Tondey, M.; Kalia, A.; Singh, A.; Dheri, G. S.; Taggar, M. S.; Nepovimova, E.; Ondrej, K. and Kuca, K. (2021). Seed priming and coating by nanoscale zinc oxide particles improved vegetative growth, yield and quality of fodder maize (*Zea mays*). Agronomy, **11**:729. https://doi.org/10.3390/agronomy11040729.

Trenkel, M. E. (2021). Slow- and controlled-release and stabilized fertilizers: An option for enhancing nutrient use efficiency in agriculture. International Fertilizer Industry Association (IFA).

Tritean, N.; Trica, B.; Dima, ª. O.; Capra, L.; Gabor, R. A.; Cimpean, A.; Oancea, F. and Constantinescu-Aruxandei, D. (2024). Mechanistic insights into the plant biostimulant activity of a novel formulation based on rice husk nano biosilica embedded in a seed coating alginate film. Front. Plant Sci., **15**:1349573. https://doi.org/10.3389/fpls.2024.1349573

Tsvigu, A.: Soropa, G.: Mtangi, W. and Mashavakure, N. (2025). Nutrient delivery to crops through fertiliser-coated seed: a systematic review. ActaAgriculturae Scandinavica, Section B-Soil and Plant Science, **75**(1). https://doi.org/10.1080/09064710.2025.2470170

Vanangamudi, K.; Srimathi, P.; Natarajan, N. and Bhaskaran, M. (2003). Current scenario of seed coating polymer. In: ICAR - short course on seed hardening and pelleting technologies for rain fed or garden land ecosystems, pp:80-100.

Vercelheze, A. E. S.; Marim, B. M. and Oliveira, A. L. M. (2019). Development of biodegradable coatings for maize seeds and their application for *Azospirillum brasilense* immobilization. Appl. Microbiol. Biotechnol., **103**:2193-2203. https://doi.org/10.1007/s00253-019-09646-w

Xie, Y.; Tang, L.; Han, Y.; Yang, L.; Xie, G.; Peng, J. and Zhang, Y. (2019). Reduction in nitrogen fertilizer applications by the use of polymer coated urea: Effect on maize yields and environmental impacts of nitrogen losses. J. Sci. Food Agric., **99**:2259-2266. https://doi.org/10.1002/jsfa.9421

Zaheer, M. S.; Ali, H. H.; Soufan, W.; Iqbal, R.; Habib-ur-Rahman, M.; Iqbal, J.; Israr, M. and Sabagh, E. L. A. (2021). Potential effects of biochar application for improving wheat (*Triticum aestivum* L.) growth and soil biochemical properties under drought stress conditions. Land, **10**(11):1125. https://doi.org/10.3390/land10111125.

Citation **K. Pravina, K. Sujatha, V. Alex Albert, P. Meenakshisundaram, G. Anand and R. Amutha (2025). Maize as a functional crop: Linking seed coating innovations to phytomedicinal and agronomic benefits. Ann. Phytomed., 14(2):177-189. http://dx.doi.org/10.54085/ap.2025.14.2.18.**