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NANO-ENGINEERED SEED COATINGS: ELECTROSPUN NANOFIBRES FOR SMART DELIVERY, VIGOROUS GERMINATION, AND STRESS TOLERANCE

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ABSTRACT

Seed quality determines crop establishment, and enhancement technologies increasingly aim to improve germination, vigour, and stress tolerance under variable environments. Conventional seed coatings, including film coating, pelleting, and hydrogel-based systems, enable dose-controlled delivery of nutrients, biostimulants, and inoculants, but face persistent limitations such as non-uniform component distribution, phytotoxicity from concentrated salts, and restricted gas exchange. Nanotechnology-based approaches, including nanoparticle and nanogel priming, improve nutrient uptake and stress tolerance but show inconsistent, sometimes phytotoxic effects and raise concerns over bioavailability and regulatory standardization. Electrospun nanofibres offer a distinct alternative, comprising continuous, nanoscale-diameter fibres with high surface-area-to-volume ratio, tunable porosity, and mechanical robustness. This review synthesizes evidence on nanofibre fabrication, polymer selection, electrospinning parameters, encapsulation and release of nutrients, phytohormones, and microbial inoculants, and agronomic and rhizosphere effects across several crops. Natural polymers such as chitosan and alginate provide biocompatibility and functional groups for encapsulation but lack water stability, whereas synthetic polymers such as PVA, PVP, and PCL provide mechanical strength and reliable spinnability; blended composite systems increasingly combine both classes. Polymer concentration, molecular weight, viscosity, conductivity, and surface tension jointly govern fibre morphology, which dictates porosity, adhesion, and release kinetics. Direct evidence shows nanofibre coatings improving germination, seedling vigour, nutrient-use efficiency, and yield relative to uncoated or conventionally coated seeds, and enabling microbial inoculant delivery with extended viability and enhanced rhizosphere colonization. However, mechanistic biochemical evidence remains sparse, seed-surface interaction is poorly characterized, and scale-up, storage stability, and cost remain unresolved. Nanofibre-based seed coating therefore represents a promising, functionally superior niche technology for localized input delivery at the earliest stage of crop establishment, rather than a validated replacement for existing seed treatments.

KEYWORDS: Nanofibre seed coating, Electrospinning, Seed germination, Controlled-release delivery, Polyvinyl alcohol (PVA), Plant growth-promoting rhizobacteria (PGPR)

1. INTRODUCTION

Seed quality is a primary determinant of crop establishment, since uniform germination and high seedling vigour decide stand establishment, early competitiveness, and final crop performance (Afzal et al., 2020). Seed enhancement is the post-harvest treatments that improve germination, seedling growth, or delivery of functional inputs at sowing (Afzal et al., 2020) because drought, salinity, and temperature extremes depress germination rate, emergence synchrony, and establishment (MacDonald & Mohan, 2025; Rhaman, 2025). Key seed-quality indicators include germination percentage, germination rate, vigour, viability, and biochemical competence linked to antioxidant activity and membrane repair(Rhaman, 2025). In tomato, halopriming with $CaCl_2$ and KNO_3 improved germination, vigour, and biochemical attributes (Akram et al., 2025), while chemical priming broadly enhances germination and stress tolerance through metabolic activation and hormone modulation (MacDonald & Mohan, 2025). Microbial seed treatments can similarly increase germination, vigour, and nutrient uptake, though responses remain crop-specific and strain-dependent (Cardarelli et al., 2022), underscoring the need for enhancement technologies that stabilize performance across variable environments (Akram et al., 2025).

Modern seed coating spans film coating, pelleting, and hydrogel-based systems, enabling uniform, dose-controlled placement of nutrients, pesticides, biostimulants, and inoculants while improving handling and sowability (Afzal et al., 2020). Slow-release NPK coatings have improved maize emergence and yield, and alginate-based coatings show low nutrient leaching with high bioavailability(Skrzypczak et al., 2021). However, limitations persist: component distribution on coated seeds can remain non-uniform even with continuous coatings (Skrzypczak et al., 2021), and nutrient coatings can induce phytotoxicity unless salts are spatially separated from the seed surface (Afzal et al., 2020). Hydrogel coatings, often assumed to aid hydration, can instead delay germination through coating stiffness and restricted gas exchange rather than impaired water transport (Phillips et al., 2025). Enhanced-efficiency coatings are further constrained by production cost and environmental impact when synthetic polymers or conventional agrochemicals are used (Biswal et al., 2026), and maintaining inoculant stability, shelf life, and sustained release at the seed–soil interface remains difficult with standard coatings (Hussain et al., 2019).

Nanotechnology has emerged as a promising response, offering high surface area, tunable surface chemistry, and enhanced interaction with biological barriers (Ali et al., 2021). Nanoparticles, nanocomposites, and nanogels serve as carriers for agrochemicals and micronutrients and as direct modulators of seed physiology (Ali et al., 2021; Muzammil et al., 2023), with nano-priming linked to faster germination, greater nutrient uptake, and improved stress tolerance (Ali et al., 2021; Rhaman, 2025). For example, POE nanogel priming improved cucumber root/shoot growth and Fe distribution, ZnO nanoparticle priming improved germination and stress mitigation at low cost (Donia & Carbone, 2023), and AgNP priming enhanced vigour via aquaporin and starch-metabolism effects(Khan et al., 2023). Yet outcomes are inconsistent: nanomaterials can be stimulatory or phytotoxic depending on particle type, size, and concentration (Ali et al., 2021), and concerns over bioavailability, toxicity, and regulatory standardization remain major adoption barriers (Muzammil et al., 2023).

Within this landscape, electrospun nanofibres represent a distinct seed-coating platform. Electrospinning generates continuous, nanoscale-diameter fibres with high surface-area-to-volume ratio and tunable morphology (J et al., 2022; Mukiri et al., 2021), enabling designed porosity that supports hydration control, protection of labile compounds, and sustained rather than surface-only release (J et al., 2022). Direct evidence, while limited, is encouraging: electrospun nanofibres have immobilized beneficial microorganisms on groundnut and canola seeds, improving germination and growth while enhancing microbial preservation (Hussain et al., 2019). GA3/IAA-loaded PVA nanofibres improved germination and vigour in blackgram (Mukiri et al., 2021), and multinutrient-loaded PVA nanofibres improved plant height and yield in green gram (J et al., 2022). Unlike conventional films, nanofibrous coatings remain porous and gas-permeable; unlike nanoparticle priming, they provide a solid-state, biodegradable scaffold co-encapsulating hormones, nutrients, microbes, and biocontrol agents (Hussain et al., 2019; Mukiri et al., 2021) though evidence remains preliminary and claims of universal superiority premature (J et al., 2022).

This review therefore examines nanofibre fabrication principles, suitable polymers, electrospinning strategies, and encapsulation/release mechanisms for delivering growth regulators, nutrients, and microbial inoculants (Hussain et al., 2019), while critically assessing germination outcomes, phytotoxicity, environmental safety, characterization, shelf life, and scale-up barriers (Biswal et al., 2026; Mukiri et al., 2021). Nanofibre-based seed coating is promising not because it is fully validated, but because it offers a plausible route beyond the constraints of conventional and nanoparticle-only treatments toward multifunctional, localized, sustained input delivery at the earliest stage of crop establishment.

2. Nature of Polymers and Electrospinning Technology for Nanofibre Seed Coating

2.1. Natural and Synthetic Polymers for Nanofibre Seed Coating

Electrospun nanofibre seed coatings draw on two broad polymer classes, each contributing distinct functional advantages and limitations. Natural polymers, polysaccharides such as chitosan, alginate, cellulose derivatives, starch, and pectin, and proteins such as gelatin, collagen, zein, and silk fibroin are attractive because of their inherent biodegradability, biocompatibility, and abundance of functional groups that facilitate encapsulation of active compounds(Dong et al., 2025; Durgadevi et al., 2025). Chitosan combines antimicrobial activity with favourable wettability and physicomechanical behaviour when electrospun (Norouzi & Abdouss, 2023), while alginate, an anionic and highly hydrophilic polysaccharide, forms porous, high-surface-area composite fibres with PVA that enhance germination and vigour in medicinal plants (Li et al., 2025). Cellulose diacetate nanofibres have been electrospun onto soybean seeds to deliver fungicides while maintaining germination at 90% or higher (Durgadevi et al., 2025), whereas carboxymethyl cellulose (CMC) requires blending with PVA and crosslinkers such as glutaraldehyde because its high viscosity and low conductivity preclude direct spinning (Haghighi et al., 2026). Zein, a hydrophobic maize protein, has produced tri-layer nanofibre architectures with encapsulation efficiencies up to 92% (Azizi et al., 2025). Despite these strengths, natural polymers generally exhibit poor water stability, rapid aqueous dissolution, and weak mechanical integrity when used alone, limiting their direct field application.

Synthetic biodegradable polymers include PVA, PVP, PEO, PCL, PLA, PLGA, and PU, compensate for these shortcomings, offering superior mechanical strength, tunable degradation, and reliable electrospinnability (Dong et al., 2025; Garcia-Barajas et al., 2026). PVA is the most widely used synthetic carrier for seed coating owing to its non-toxicity, semicrystalline structure, and excellent fibre-forming capacity (Garcia-Barajas et al., 2026; Mukiri et al., 2021). PVP coatings on cowpea seeds improved germination relative to film coatings through porous, gas-permeable structures (Durgadevi et al., 2025), while hydrophobic PCL has been paired with zinc oxide nanoparticles and CMC for controlled-release coatings (Durgadevi et al., 2025; Haghighi et al., 2026). PLA nanofibres have delivered plant growth regulators to lettuce seeds with slow, low-leaching release (Durgadevi et al., 2025). However, synthetic polymers can show unpredictable biocompatibility and, in the case of PVP, high cost and poor moisture-barrier properties (Badgar et al., 2022; Dong et al., 2025).

Because neither class alone satisfies all seed-coating requirements, blending, crosslinking, and composite formation are essential strategies. PVA/chitosan blends produce smooth, bead-free fibres with tunable hydrophobicity (Turanlı et al., 2025); alginate/PVA composites integrate agrochemicals while modulating soil microbiota (Li et al., 2025); and PVA/PCL core–shell architectures allow an outer hydrophobic barrier to regulate diffusion (Garcia-Barajas et al., 2026; Hussein et al., 2021), Such hybrid systems combine the biological compatibility of natural polymers with the mechanical and processing robustness of synthetic polymers, making them particularly suited to seed coatings that must withstand handling and sowing while remaining biodegradable and non-phytotoxic.

2.2. Polymer Properties Affecting Nanofibre Formation

Continuous, uniform nanofibre formation depends on a set of interrelated polymer molecular properties: molecular structure, molecular weight, chain entanglement, polymer-solvent interaction, functional groups, crystallinity, hydrophilicity, and charge density (Badgar et al., 2022; Mukiri et al., 2021). Of these, chain entanglement is the most critical determinant of continuous fibre formation, often outweighing molecular weight itself; polymers capable of strong quadruple hydrogen bonding can electrospin like much larger nonfunctional polymers even at modest molecular weight (Al-Abduljabbar & Farooq, 2022). Solution viscosity remains a more general indicator of spinnability, since some low-molecular-weight ceramic precursor solutions can still be electrospun (Al-Abduljabbar & Farooq, 2022)(Figure 1.1).

The relationship between entanglement and fibre quality follows a defined continuum. Insufficient entanglement cannot sustain jet continuity and yields droplets or electrospray; moderate entanglement produces beaded fibres because the network cannot fully resist capillary-instability-driven jet breakup; optimal entanglement yields continuous, bead-free fibres capable of withstanding the whipping instability; and excessive entanglement or viscosity resists jet stretching, producing irregular, large-diameter fibres and unstable processing (Al-Abduljabbar & Farooq, 2022; Haghighi et al., 2026)

These molecular characteristics converge on three solution parameters are viscosity, electrical conductivity, and surface tension that jointly govern Taylor-cone formation, jet stability, jet stretching, fibre diameter, bead formation, uniformity, porosity, and mechanical strength (Badgar et al., 2022; Colín-Orozco et al., 2024). Molecular weight and concentration interact to set the critical entanglement concentration: higher-molecular-weight polymers reach sufficient entanglement at lower concentrations, whereas lower-molecular-weight polymers require higher concentrations to achieve comparable spinnability (Al-Abduljabbar & Farooq, 2022). Functional groups and charge density influence conductivity directly; ionic or ionisable polymer groups increase Coulombic repulsion within the jet, promoting stretching and thinner fibres (Colín-Orozco et al., 2024). Crystallinity and hydrophilicity shape both polymer-solvent compatibility during spinning and the finished fibre's water-uptake behaviour, porosity, and mechanical strength (Garcia-Barajas et al., 2026).

These morphological outcomes translate directly into seed-coating performance. High porosity and surface area from optimally entangled fibres promote seed-surface adhesion and water uptake (Li et al., 2025), while the open, porous architecture supports gas exchange more effectively than continuous conventional films, which tend to restrict oxygen diffusion and induce burst-release behaviour (Colín-Orozco et al., 2024; Durgadevi et al., 2025). Active-ingredient loading and release kinetics are further governed by crystallinity and polymer–active interactions, as shown by urea-loaded PVA fibres, where reduced crystallinity and hydrogen bonding between PVA chains and urea produced a 100-hour induction period before multiphase release (Garcia-Barajas et al., 2026). Coating persistence likewise depends on polymer chemistry, with PNCMC (CMC/PVA/glutaraldehyde) fibres degrading 93.6% in phosphate-buffered saline over 30 days compared with only 33.7% for PCL-based fibres (Haghighi et al., 2026), underscoring that molecular-level polymer properties ultimately dictate field-relevant coating behaviour.

2.3. Polymer Concentration and Molecular Weight

Polymer concentration governs nanofibre morphology through its direct influence on chain entanglement and solution viscosity, following a well-documented, progressive pattern (Colín-Orozco et al., 2024; Mukiri et al., 2021). At sub-threshold concentrations, entanglement density is insufficient to sustain jet continuity, producing droplets, electrospray, or discontinuous, beaded fibres. For example, 5% (w/v) PVA at 85,000 g/mol molecular weight produces bad spraying and discontinuous fibres, while 6% PVA at the same molecular weight still yields only limited fibre formation (Haghighi et al., 2026). As concentration increases, greater chain entanglement stabilises the jet and enables continuous fibre formation, though fibre diameter simultaneously increases because more polymer mass is deposited per unit jet (Colín-Orozco et al., 2024). Ten percent (w/v) PVA at 124,000 g/mol represents an optimal formulation, generating the most uniform, bead-free fibres, whereas 15% PVA at the same molecular weight is likely excessively viscous, impeding adequate jet stretching and again compromising uniformity (Haghighi et al., 2026).

Molecular weight interacts closely with concentration in determining electrospinnability. Because longer polymer chains have a higher probability of interchain overlap, higher-molecular-weight polymers achieve sufficient entanglement at comparatively lower concentrations (Al-Abduljabbar & Farooq, 2022). This interaction is illustrated directly: 10% PVA at 124,000 g/mol yields uniform fibres, whereas 10% PVA at the lower molecular weight of 85,000 g/mol does not (Haghighi et al., 2026). Commercially available PVA grades used in seed-coating research typically fall within a molecular weight range of 85,000–125,000 g/mol, with a degree of polymerisation of 1,700–1,800 and 98–99% hydrolysis (Garcia-Barajas et al., 2026). Under these conditions, 10% PVA produces fibre diameters of 111–176 nm, while incorporation of plant hormones increases fibre diameter further, to 131–296 nm for GA_3-loaded fibres and 106–275 nm for IAA-loaded fibres, reflecting the additional mass and altered solution rheology introduced by the active ingredient (Raja et al., 2020).

Because optimal concentration and molecular weight depend on the specific polymer–solvent system, applied voltage, flow rate, solution conductivity, temperature, and relative humidity, no universal optimum exists across formulations (Badgar et al., 2022). Changing one parameter typically necessitates re-optimising others; increasing urea loading in PVA nanofibres, for instance, simultaneously increases surface roughness, reduces fibre diameter, and lowers crystallinity, altering both morphology and release kinetics (Garcia-Barajas et al., 2026). These parameters carry direct agronomic consequences: soybean seeds coated for 2, 3, and 4 hours maintained germination rates of 90% or higher regardless of coating thickness, indicating that coating duration and resulting thickness did not compromise germination, although the coating thickness required for optimal porosity and controlled release must still be determined empirically for each polymer–active combination (Durgadevi et al., 2025).

2.4. Viscosity, Electrical Conductivity and Surface Tension

Viscosity, electrical conductivity, and surface tension are the three solution-level parameters most directly responsible for jet initiation, stability, and the resulting fibre morphology in electrospinning (Badgar et al., 2022). Viscosity, which arises from polymer concentration, molecular weight, and chain entanglement, determines whether the polymer jet can sustain continuous elongation under the whipping instability rather than fragmenting into droplets. At low viscosity, insufficient viscoelastic resistance allows surface tension to dominate, breaking the jet into beads or particles; at excessively high viscosity, the solution resists stretching, causing irregular, thick fibres or clogging at the spinneret (Al-Abduljabbar & Farooq, 2022). Between these extremes lies a viscosity range that supports continuous, uniform, bead-free fibre formation, consistent with the concentration-dependent trends described for PVA systems above (Haghighi et al., 2026).

Electrical conductivity governs the net charge density carried by the polymer jet and, consequently, the magnitude of Coulombic repulsion that drives jet elongation and thinning under the applied electric field. Polymers or additives bearing ionisable or ionic functional groups raise solution conductivity, intensifying charge repulsion within the jet, promoting greater stretching, and yielding thinner fibres with reduced bead frequency (Colín-Orozco et al., 2024). Conversely, low-conductivity solutions, such as unmodified CMC, generate weak Coulombic forces insufficient to overcome surface tension, resulting in poor or non-uniform fibre formation unless conductivity is enhanced through blending or ionic modification (Haghighi et al., 2026).

Surface tension acts as the principal resisting force that the applied electric field must overcome to initiate and sustain the Taylor cone at the spinneret tip. High surface tension favours the formation of spherical droplets or beaded fibres because the solution minimises its surface area per unit mass; reducing surface tension, whether through solvent selection, polymer-solvent interaction, or surfactant addition, favours smooth, continuous fibre formation and a lower incidence of jet breakup (Badgar et al., 2022).

These three parameters do not act independently but interact continuously during jet formation: adequate conductivity and moderate surface tension are required to establish a stable Taylor cone, while appropriate viscosity is required to maintain jet continuity once elongation begins under the whipping instability (Colín-Orozco et al., 2024). For nanofibre seed coatings, this interaction has direct practical consequences, since fibre diameter, bead density, and surface uniformity determined by this viscosity–conductivity–surface-tension balance in turn control the porosity, adhesion, and gas-exchange properties that influence hydration and germination performance at the seed surface (Durgadevi et al., 2025; Haghighi et al., 2026). Rational formulation of nanofibre seed coatings therefore requires simultaneous control of all three solution parameters rather than optimisation of any single variable in isolation.

3. Loading, Release, and Physiological/Biochemical Effects of Active Compounds

3.1. Nutrient and Micronutrient Delivery

Electrospun nanofibre seed coatings incorporate active compounds either by direct blending of soluble cargos into the spinning dope or by embedding particulate reservoirs within the polymer matrix, enabling localized delivery at the seed–soil interface after imbibition (V. Krishnamoorthy et al., 2016; Mohanraj et al., 2024). Direct evidence from green gram shows that 10% PVA nanofibres carried recommended doses of macro-, micro-, and trace nutrients, delivering approximately 20–25 mg of nutrient-fortified nanofibre per seed and sustaining nutrient retention and slow release for up to 35 days, indicating that nanofibres can act as true controlled-release depots rather than transient surface films (Mohanraj et al., 2024). This multinutrient PVA system increased green gram field emergence from 62% to 99.8%, root length from 12.3 to 27.1 cm, shoot length from 28.7 to 47.7 cm, dry matter from 16.2 to 27.5 g, and grain yield from 621.6 to 796.3 kg ha^{-1} relative to uncoated controls (Mohanraj et al., 2024). A related field application of 10% PVA nanofibres loaded with primary, secondary, and micronutrients produced a plant height of 44.97 cm, grain yield of 854.2 kg ha^{-1}, and haulm yield of 1100 kg ha^{-1} (J et al., 2022), reinforcing that localized nutrient placement improves nutrient-use efficiency relative to broadcast application.

Micronutrient-specific delivery is best documented for zinc. Cellulose acetate nanofibres loaded with 100 mg L^{-1} ZnO nanoparticles produced bead-free fibres of 526 ± 139 nm with 94% porosity, raising aerobic rice germination to 60% at day 3 and 67% at day 7, outperforming both unloaded CA fibres and uncoated seeds (Zaim et al., 2022).

PVP nanofibres co-loaded with urea and cobalt nanoparticles achieved controlled release and superior cowpea germination relative to uncoated or singly loaded coatings (Krishnamoorthy & Rajiv, 2021), building on earlier work in which PVP–urea–CoNP fibres were characterized by FTIR, SEM, XRD, and TGA, confirming polymer–nutrient interaction and establishing the feasibility of PVP as a biocompatible carrier for nutrient-fortified coatings (V. Krishnamoorthy et al., 2016).

Beyond nutrients, crop-protection and antioxidant actives follow analogous release logic. Copper-releasing biopolymer nanofibres improved tomato and lettuce germination under *Fusarium*-infected conditions and increased seedling biomass by 12–29% relative to healthy controls, while requiring only small quantities of active compound compared with conventional film coatings (Xu et al., 2020). Cellulose diacetate nanofibres loaded with the fungicides abamectin and fluopyram, electrospun directly onto soybean seeds, remained structurally stable in water for more than two weeks without impairing germination, released both actives slowly and sustainably, and retained fungicidal activity against *Alternaria lineariae* (Farias et al., 2019). Antioxidant delivery has similarly been demonstrated in PCL nanofibre films containing gallic-acid-loaded mesoporous silica (32.3% gallic acid loading), where the 10% formulation achieved 100% corn germination and a 70% higher bean germination rate than the control while maintaining high water-vapour permeability (An et al., 2025). Collectively, these studies show that polymer composition governs release rate of hydrophilic PVA, PVP, or alginate/PVA matrices swell rapidly and promote ion diffusion, whereas more hydrophobic systems such as PCL or cellulose acetate moderate dissolution and prolong release (Zaim et al., 2022) and that this tunability translates directly into reduced input quantities and improved delivery precision compared with conventional coatings.

3.2. Phytohormone (Plant Growth Regulator) Delivery

Gibberellic acid (GA_3) and indole-3-acetic acid (IAA) are the most extensively studied phytohormones in nanofibre seed-coating research. GA_3 breaks dormancy, stimulates hydrolytic enzyme activity, promotes endosperm mobilization, and enhances radicle and shoot emergence, while IAA promotes root initiation and elongation, cell expansion, and early seedling development through accelerated nutrient uptake from the rhizosphere (Kanta et al., 2026). The clearest direct nanofibre evidence comes from electrospun PVA carriers: a 10% PVA system produced fibres of 111–176 nm, and hormone loading increased fibre diameter to 106–275 nm for IAA and 131–296 nm for GA_3, confirming physical incorporation of the hormones within the fibrous carrier (Raja et al., 2020). IAA-loaded nanofibre-coated seeds achieved 88% germination in groundnut and 86% in black gram, with seedling-vigour indices of 3458 and 3431, respectively, and maintained superior germination and vigour under PEG-induced moisture stress, indicating that nanofibre-mediated hormone delivery remains functional under water deficit during early establishment (Raja et al., 2020).

Complementary direct evidence extends this platform to other crops and hormone forms. GA_3-loaded electrospun microcapsules applied to fresh and aged maize seeds using 15% PVA with a fibre diameter of 281 nm and a GA_3 loading of 100 ppm were particularly effective in aged seeds, improving germination to 80%, seedling length to 23 cm, and seedling dry weight to 0.53 g (Bhaskar et al., 2024), demonstrating that nanofibre-delivered GA_3 can partially restore vigour lost to seed ageing. In roselle, IAA, GA_3, and chitosan nanofibre treatments altered physio-morphological characteristics and metabolite content in a concentration-dependent manner, providing further direct support that nanofibrous hormone carriers modulate seedling physiology beyond simple germination stimulation (Mirheidari et al., 2022)(Figure 1.2).

Related, non-nanofibre evidence helps contextualize these effects that is, nanoencapsulation of GA_3 in alginate/chitosan nanoparticles, rather than nanofibres, enhanced seed-priming benefits under water-deficit conditions in tomato: 5 $\mu g\ mL^{-1}$ nano-GA_3 reduced photosystem II damage by 14% and stomatal conductance loss by 13%, reduced water loss by 38%, and increased instantaneous carboxylation efficiency by 24% (Fregonezi et al., 2024), illustrating the physiological ceiling that a nanofibre-based GA_3 delivery system might likewise approach if translated to a fibrous carrier. Conventional (non-nanoparticle) IAA seed coating at 50 ppm improved soybean biochemical composition, raising oil and protein content relative to untreated seeds (Kalpande et al., 2020), indicating that hormone seed treatments can influence downstream seed biochemistry independent of the delivery platform. At the mechanistic level, GA_3 and IAA (10 μM) alleviated cadmium toxicity in chickpea seedlings by restoring Ca^{2+} homeostasis and activating Ca^{2+}-signalling genes (*ABP19a*, *MAPK2*, *CDPK1*, *CaM*), thereby reducing Cd uptake, oxidative stress, and growth inhibition (Sakouhi et al., 2024); a stress-protective function that would be a logical, though not yet directly tested, target for controlled-release nanofibre delivery under heavy-metal contaminated soils.

Mechanistically, these responses are consistent with rapid nanofibre hydration after seed imbibition, which maintains close contact between the hormone reservoir and the seed surface. The high surface-area-to-volume ratio and porosity of electrospun fibres favour uniform wetting, short diffusion paths, and gradual release rather than immediate loss to the surrounding medium (Mukiri et al., 2021), keeping hormone concentrations near the emerging radicle within an effective physiological range. Direct nanofibre evidence for cytokinins such as kinetin or BAP, and for IBA, remains sparse in the available literature, so their relevance to nanofibre delivery is presently inferential rather than demonstrated.

3.3. Biochemical, Metabolic, and Stress-Response Effects

Direct biochemical evidence from nanofibre seed coatings remains considerably thinner than the growth-response literature. The strongest direct study is the alginate/PVA composite coating for *Astragalus membranaceus*, where integrated pesticides and fertilizers improved germination and seedling biomass while significantly upregulating defense-related enzymes in pot experiments, alongside shifts in rhizosphere microbial-community composition (Li et al., 2025). A second direct example is the zinc-reinforced pectin/PVA/collagen nanostructure, in which controlled Zn release boosted superoxide dismutase activity and conferred oxidative-stress protection while approximately doubling tomato seedling growth after an initial 8-day germination delay (Sharma et al., 2025), mechanistically plausible given Zn's role as a cofactor for redox-active enzymes, with gradual nanofibre release expected to reduce the burst toxicity associated with soluble Zn salts or concentrated nanoparticle priming.

For most other stress-response endpoints, reactive oxygen species (ROS) regulation, lipid peroxidation, osmolyte accumulation, and hormonal cross-talk, the evidence remains largely indirect. IAA-loaded PVA nanofibres improved germination and vigour under PEG-induced moisture stress in groundnut and black gram, implying enhanced osmotic adjustment, but the underlying study did not report H_2O_2, MDA, proline, soluble sugars, or antioxidant-enzyme activities directly (Raja et al., 2020). The calcium-signalling mechanism identified for GA_3/IAA in cadmium-stressed chickpea (Sakouhi et al., 2024)and the photosynthetic and water-relations improvements from nanoencapsulated GA_3 under drought in tomato (Fregonezi et al., 2024)similarly provide mechanistic plausibility rather than direct confirmation within a nanofibre delivery system. Indirect support for redox-related endpoints also comes from nanocellulose-based Fe/Zn nanopriming in cotton, where 50 ppm Fe/CMF and 200 ppm Zn/CMF improved drought performance while increasing SOD, CAT, and POD activity, raising proline content, and lowering H_2O_2 and MDA (Hamid et al., 2026); because this was nanopriming rather than electrospun seed coating, it supports the biochemical mechanism without establishing direct translatability. The central knowledge gap that emerges is that nanofibre seed-coating studies rarely quantify molecular and metabolic endpoints, leaving the field short of direct causal evidence linking seed-surface release kinetics to ROS homeostasis, hormonal signalling, and stress-responsive gene expression during germination and early establishment (Dey et al., 2026).

4. Comparative Performance and Microbial (PGPR) Delivery in Nanofibre Seed Coatings

4.1. Comparison between Conventional coating and Nanofibre Coating

Conventional seed coatings - film coating, encrustment, pelleting, and bulk polymer layers — remain widely used because they are operationally familiar and scalable, but they often rely on larger material inputs and can deliver active ingredients inefficiently (Zaim et al., 2023). Electrospun nanofibre coatings, by contrast, generate ultrathin, highly porous, high-surface-area architectures that promote rapid hydration, ion transport, and gas exchange around the seed surface (Dey et al., 2026; Zaim et al., 2022). These structural differences are mechanistically important: porous nanofibre layers provide shorter diffusion paths and better oxygen permeability than dense films, improving imbibition and metabolic activation during early germination (Dey et al., 2026; Krishnamoorthy & Rajiv, 2018).

Direct comparisons support these advantages without justifying claims of universal superiority. In cowpea, electrospun PVP fibres outperformed film coatings because the fibrous layer enabled steady nutrient release and better gas exchange through seed pores, whereas the film caused burst release and more limited gaseous diffusion (Vidya Krishnamoorthy et al., 2016). In black gram, nutrient-loaded PVA–PVP nanofibrous coatings reached 100% germination within 24 hours, while uncoated seeds required approximately 120 hours to reach the same value (Dey et al., 2026). In *Astragalus*, alginate/PVA electrospun coatings outperformed conventional film coating in both germination and seedling biomass while offering better environmental compatibility (Li et al., 2025). A further line of comparative evidence comes from surface-functionalized nanofibres applied without a conventional-coating comparator but still illustrating the performance ceiling of nanostructured seed treatments: chitooligosaccharide-coated silica nanofibres (10–100 nm diameter) increased peanut germination from 0.789 to 0.989 and root length from 81.8 to 119 mm after 7 days, and increased date palm germination from 0.79 to 0.97, root length from 11.5 to 23.1 mm after 17 days, and leaf length from 128.6 to 228.7 mm after 30 days, improvements greater than those obtained with chitosan alone or uncoated silica nanofibres (Nam et al., 2025).

Nanofibre coatings also allow more flexible loading of sensitive or low-dose compounds. Hormones, microbes, antioxidants, and multinutrient salts have all been incorporated successfully into electrospun matrices, and their high inter- and intra-fibre porosity can enhance microbial and nutrient delivery relative to denser conventional coatings(Mukiri et al., 2021; Raja et al., 2020). Yet several limitations persist. Electrospinning requires specialized high-voltage equipment and careful optimization of voltage, flow rate, tip-to-collector distance, and solvent systems (An et al., 2025); mechanical integrity can deteriorate at high additive loading, as observed when 10% nanoparticle incorporation approached the practical upper limit for uniform PCL fibres (An et al., 2025); and scale-up, coating uniformity across large seed lots, storage stability, polymer cost, and field validation remain comparatively underdeveloped relative to industrial pelleting or film coating (Del Pilar Pramparo et al., 2025; Singh et al., 2024). The strongest current evidence therefore supports nanofibre coatings as a functionally superior niche platform for controlled, localized delivery rather than a universal replacement for conventional seed-treatment technologies.

4.2. Polymer–Microbe Compatibility and Biocompatible Nanofibre Engineering

Electrospun nanofibres can immobilize plant-growth-promoting microorganisms (PGPR) directly within polymer matrices, converting the coating into both a physical seed cover and a living inoculant reservoir (Del Pilar Pramparo et al., 2025; Mukiri et al., 2021). The best-supported matrices are aqueous PVA systems, which combine electrospinnability, biodegradability, hydrophilicity, non-toxicity, and mild processing conditions compatible with living cells (Mukiri et al., 2021)). Designing such matrices requires reconciling two partly competing objectives:

preserving microbial viability during loading, spinning, drying, and storage, while still enabling controlled release and metabolic reactivation once the seed contacts soil moisture. Biocompatibility is therefore paramount, the polymer must avoid direct toxicity to the encapsulated organism and must also support the resumption of metabolic activity after germination.

Several polymer-level mechanisms explain why PVA performs well in this dual role. Rapid solvent evaporation during electrospinning limits microbial exposure to potentially toxic solvents, improving survival relative to conventional encapsulation methods (Diep & Schiffman, 2021). Polymer matrices with a glass-transition temperature (Tg) above ambient temperature remain in a glassy state after drying, restricting molecular mobility and microbial metabolism until hydration initiates reactivation, effectively placing encapsulated cells in a dormant, storage-stable state (Diep & Schiffman, 2021). PVA also provides better seed adhesion than more hydrophobic polymers such as PCL (Xu et al., 2020), and the porous nanofibrous network creates mechanical interlocking with seed-surface irregularities that supplements this chemical adhesion. Crosslinking strategies, such as glutaraldehyde-crosslinked PVA–alginate systems, have been reported to further improve seed-coat binding while maintaining controlled-release behaviour (Meng et al., 2023). Unlike dense conventional film coatings, the interconnected pores of electrospun nanofibres facilitate oxygen and carbon dioxide exchange, supporting adequate seed respiration during germination and avoiding the hypoxic conditions that dense films can create (Meraz-Dávila et al., 2021), while simultaneously regulating water uptake through capillary action — moderating rapid imbibition that could otherwise damage membranes in sensitive seeds (Xu et al., 2020). The large surface area of the fibrous matrix accelerates hydration and triggers polymer dissolution or swelling that releases encapsulated PGPR in response to soil moisture (Chakkalakkal et al., 2022), with release timed to coincide with radicle emergence and thereby maximize the probability of immediate root colonization (Mukiri et al., 2021).

Functional outcomes attributed to this engineering are evident across several PGPR–polymer systems. *Methylorubrum aminovorans*-loaded PVA nanofibres improved groundnut germination and drought tolerance through controlled release of metabolically active bacteria (Mukiri et al., 2021), while *Pseudomonas urmiensis*-loaded PVA nanofibres improved soybean seedling vigour and biomass relative to both free bacterial treatments and uncoated controls (Del Pilar Pramparo et al., 2025). PVA–PVP–glycerol composite coatings maintained *Bacillus subtilis* viability under ambient storage conditions, underscoring the importance of polymer selection, beyond PVA alone for long-term inoculant preservation (Hussain et al., 2019). Alginate/PVA composites similarly provide highly biodegradable, biocompatible coatings for medicinal plant seeds, enhancing germination, seedling vigour, and rhizosphere microbial composition (Li et al., 2025). Taken together, this evidence indicates that biocompatible nanofibre engineering for microbial delivery depends on a coordinated set of polymer properties hydrophilicity, glass-transition behaviour, adhesion, porosity for gas and water exchange, and hydration-triggered release rather than any single material characteristic in isolation.

4.3. Microbial Survival, Root Colonization, and Plant-Growth Promotion

The central challenge in microbial nanofibre seed coatings is preserving viability through electrospinning, drying, storage, and rehydration, and then achieving timely release and rhizosphere establishment after sowing. Outcomes depend strongly on microbial physiology, particularly whether the organism is spore-forming. In soybean, an aqueous PVA coating preserved the spore-forming *Bacillus pumilus* SF5 for over six months, while the more fragile, non-sporulating *Pseudomonas urmiensis* AW4 remained viable for more than seven days, compared with only three days under standard inoculation (Del Pilar Pramparo et al., 2025), indicating that the high-voltage electrospinning field itself is not necessarily lethal when the formulation is aqueous and the organism is physiologically resilient.

The *Methylorubrum aminovorans*–groundnut system provides the most detailed storage data available. Viable counts declined from an initial 6.6×10^5 CFU g^{-1} nanofibre (from a starting inoculum of 1×10^8 CFU) to 1.85×10^5, 2.2×10^4, and 1.2×10^4 CFU g^{-1} after 10, 20, and 30 days of ambient storage, respectively (Mukiri et al., 2021). Despite this decline, coated seeds showed higher germination, root and shoot length, seedling vigour, dry-matter production, plant biomass, root volume, nodule number, and fresh nodule weight than controls, with growth promotion attributed to effective root colonization following localized delivery from the nanofibres (Mukiri et al., 2021). Comparable functional outcomes have been reported for other PGPR taxa immobilized in electrospun nanofibres. *Pantoea agglomerans* ISIB55 and *Burkholderia caribensis* ISIB40 immobilized on soybean seeds maintained bacterial viability for up to 30 days of storage and facilitated subsequent root colonization after sowing; *P. agglomerans* improved seed germination, root length, and root dry weight, while *B. caribensis* increased leaf number and shoot dry weight, demonstrating that different PGPR taxa can confer distinct, complementary growth benefits from the same nanofibre delivery platform (P. R. De Gregorio et al., 2017). PVA/PVP nanofibres co-loaded with *Bacillus subtilis* and *Serratia marcescens* protected both organisms for 15 days at room temperature and enabled sustained release, improving canola germination, root development, biomass, and rhizosphere microbial establishment (Hussain et al., 2019). Innovative rice seed coatings combining polymer nanofibres and microparticles via electrospinning have further extended this approach toward cereal crops (Castañeda et al., 2014), and hydrogel-based (non-electrospun) biocontrol coatings, such as an alginate/pectin hydrogel containing *Bacillus subtilis* ZF71 that maintained high bacterial viability for 37 days and achieved 53.26% control of *Fusarium* root rot (Abdukerim et al., 2024), provide a useful biopolymer-based benchmark against which nanofibre biocontrol efficacy can be compared.

Following seed imbibition and germination, the hydrophilic nanofibre matrix facilitates gradual microbial release into the surrounding soil, promoting the establishment of beneficial bacteria close to emerging roots (Castañeda et al., 2014). Because microorganisms are positioned directly on the seed at sowing, this approach offers a more targeted delivery route to the developing rhizosphere than conventional soil or foliar application, potentially reducing microbial loss and improving early root colonization (P. R. De Gregorio et al., 2017). At the same time, microbial seed coating remains a low-dose, targeted delivery strategy whose broader adoption is constrained by microbial viability, formulation compatibility, shelf life, and unresolved field-scale performance (Rocha et al., 2019). Across the evidence assembled here, PVA-based aqueous nanofibres emerge as the most credible platform for living seed inoculants, spore-forming bacteria consistently outperform non-sporulating strains in post-encapsulation viability, and functional benefits improved germination, root and shoot growth, nodulation, and biomass are reproducible across multiple PGPR genera (*Methylorubrum*, *Pseudomonas*, *Bacillus*, *Pantoea*, *Burkholderia*, *Serratia*). Direct nanofibre evidence for fungal biocontrol agents or mycorrhizae remains absent from the available corpus, leaving broader polymer–microbe compatibility, and translation from laboratory storage data to field-relevant shelf-life and colonization performance, as open questions for future research.

5. Mechanism of Microbial Nanofibre Seed Coatings in Root Modulation and Abiotic-Stress Tolerance

After sowing, microbial nanofibre seed coatings can establish a spatiotemporally regulated microbial microenvironment around the germinating seed and emerging radicle. Hydration of hydrophilic polymers causes fibre swelling, polymer-chain relaxation and gradual release of encapsulated microorganisms, thereby positioning beneficial bacteria close to the developing root during the critical stages of seedling establishment (Hussain et al., 2019). Unlike conventional inoculation, in which microbial cells may rapidly disperse into the surrounding soil, the nanofibre matrix can function as a temporary microbial reservoir at the seed–soil interface. This localized delivery increases the opportunity for bacterial attachment and root colonization and may determine the intensity and duration of subsequent plant–microbe interactions (P. De Gregorio et al., 2017).

A potentially important mechanism linking localized bacterial establishment with plant responses is quorum sensing (QS). QS is a population-density-dependent communication process in which bacteria produce and perceive signal molecules that regulate collective behaviours after signal concentrations reach effective thresholds. These behaviours include biofilm formation, surface attachment, metabolite production and other functions associated with rhizosphere colonization (Afridi et al., 2023; Kumar et al., 2026). In *Pantoea alhagi*, disruption of the *luxS* gene reduced autoinducer-2 production, biofilm formation and root colonization, demonstrating that QS can directly regulate bacterial establishment on plant roots (Lin et al., 2025). Furthermore, AI-2-mediated microbial communication has been associated with cooperative interactions among beneficial bacteria and improved drought tolerance in wheat (Lin et al., 2025) (Figure1.3).

In the context of nanofibre seed coatings, controlled microbial release may create the localized population densities required for QS activation. The hydrated fibre matrix can retain bacteria near the seed and emerging root, while root exudates provide nutrients and signalling compounds that influence microbial activity and rhizosphere community assembly (Afridi et al., 2023; Sharma et al., 2023). QS-mediated coordination may subsequently promote persistent root attachment, biofilm development and production of microbial metabolites. These processes can influence plant hormonal signalling, particularly through bacterial indole-3-acetic acid (IAA) production, thereby modifying primary-root elongation, lateral-root initiation and root branching (Khan et al., 2021). In soybean, both *Pantoea agglomerans* ISIB55 and *Burkholderia caribensis* ISIB40 produced IAA, although their effects on plant growth differed, with *P. agglomerans* increasing root length and root dry weight (P. De Gregorio et al., 2017).

Modification of root architecture can directly contribute to abiotic-stress tolerance by increasing the soil volume explored by roots and improving water and nutrient acquisition. Under drought, microbial biofilms and extracellular polymeric substances can enhance water retention around roots, while beneficial microorganisms can promote root development and improve plant water relations (Paravar et al., 2023). *Methylobacterium aminovorans* delivered through PVA nanofibres improved groundnut germination, root volume and drought tolerance, suggesting that localized microbial delivery can contribute to stress adaptation (Mukiri et al., 2021). Under salinity, microbial seed coatings can additionally influence osmotic adjustment and ionic homeostasis. For example, *Serratia nematodiphila*-based seed coating modulated proline and soluble sugars and improved Na^+/K^+ homeostasis in maize under salt stress (Cheng et al., 2025). Similarly, a silk fibroin–trehalose system containing *Rhizobium tropici* supported root infection and nodulation while mitigating soil-salinity effects in common bean (Zvinavashe et al., 2021).

6. Release kinetics

6.1 Nutrient Release, Water Absorption and Factors Affecting Delivery

Direct evidence from electrospun seed coatings shows that nutrient release is initiated when water enters the fibrous matrix, hydrates the polymer, and opens diffusion pathways for dissolved ions or low-molecular-weight actives (Dey et al., 2026). In hydrophilic systems, this process can include polymer swelling and partial dissolution; PVA–PVP coatings were explicitly linked to rapid hydration, ionic mobility, and diffusion-mediated nutrient transport during seed imbibition (Dey et al., 2026). PVA seed coatings carrying multinutrients for green gram used fibres of 260–540 nm (Mohanraj et al., 2022), while a related biodegradable PVA system incorporating N, P, K, Ca, Mg, S, Fe, B, and Zn showed nutrient-loaded fibres expanding from 130 nm to 268–400 nm, consistent with encapsulation-induced morphological change (Mohanraj et al., 2022). Nitrogen delivery is best documented: in non-seed PVA/urea nanofibres, higher urea loading produced a 100 h induction period followed by multiphase diffusion and quasi-steady release by 750–800 h, indicating that internal polymer–solute interactions can retard dissolution despite the hydrophilic matrix (Garcia-Barajas et al., 2026).

Micronutrient evidence is stronger than P or K-specific evidence in direct seed-coating studies. Cellulose acetate/ZnO nanofibres for aerobic rice combined 526 ± 139 nm fibres with 94% porosity and a contact angle of 131 ± 2°, and the best formulation raised germination to 60% at 3 d and 67% at 7 d (Zaim et al., 2022). In cowpea, electrospun PVP coatings incorporating urea and cobalt nanoparticles also achieved controlled nutrient delivery during germination, although the available evidence is qualitative rather than kinetic (Krishnamoorthy & Rajiv, 2021). Active-compound release is also tunable for non-nutrient cargo: gallic-acid-loaded PCL fibres showed pH-responsive, near-complete release with an initial burst followed by sustained release, and acidic media slowed diffusion (An et al., 2025). Across studies, fibre diameter, porosity, polymer concentration, and composition alter water ingress and therefore release rate, but direct seed-coating evidence for crosslinking, soil pH, and temperature effects remains sparse and is still inferred largely from broader nanofibre or hydrogel literature rather than from field-tested seed systems (Phillips et al., 2025).

6.2 Sustained versus Rapid Delivery: Advantages, Limitations and Applications

Electrospun seed coatings can generate either rapid release, sustained release, or a hybrid profile, and the available evidence suggests that no single kinetic pattern is universally optimal (An et al., 2025; Durgadevi et al., 2025). Rapid release can be advantageous when compounds are needed during early imbibition. In the gallic-acid/PCL system, the initial burst was mechanistically aligned with the first 0–48 h water-uptake phase, when antioxidant protection could buffer ROS and support uniform germination (An et al., 2025). Likewise, nutrient-loaded PVA–PVP coatings accelerated black gram germination from ~120 h in controls to 24 h for coated seeds, implying that early nutrient availability and rapid hydration can be biologically beneficial (Dey et al., 2026). However, burst release from highly hydrophilic matrices can also increase leaching risk and create short-lived nutrient pulses; this limitation was specifically noted for PVP/urea systems (Durgadevi et al., 2025; Fernando et al., 2023).

Sustained delivery is advantageous when actives must remain available beyond imbibition. Reviews of direct seed-coating studies report two-week pesticide release from cellulose diacetate nanofibres and slower microbial or fungal inoculant delivery at the seed–soil interface, supporting the logic of prolonged local availability (Fernando et al., 2023). In green gram, multinutrient PVA nanofibre seed coatings improved field performance, including seed yield of 883.41 kg ha^{-1}, consistent with improved nutrient-use efficiency but not, by itself, proof of the exact release kinetics operating in soil (Mohanraj et al., 2022). Slower release is therefore not inherently superior: phytohormones or antioxidants may require an early pulse, whereas N fertilizers, micronutrients, pesticides, or inoculants may benefit from staged delivery (Ullah et al., 2026). Key limitations remain dependence on soil moisture, possible incomplete release, storage losses for living inoculants within 15 days, and unresolved scale-up, cost, and reproducibility issues despite claims of manufacturability (Garcia-Barajas et al., 2026; Ullah et al., 2026). The major gap is the lack of studies that directly correlate laboratory release curves with nutrient uptake, germination, and field performance under realistic soils (Durgadevi et al., 2025).

7. Seed Interaction with nano-fibre

7.1 Seed Surface Characteristics, Adhesion and Surface Morphology

The interaction between an electrospun coating and the seed is governed first by seed-surface heterogeneity, yet this remains one of the least characterized variables in the literature. Direct seed-coating studies show that electrospinning can form conformal and relatively uniform surface layers: nutrient-loaded PVA–PVP fibres were described as conformally deposited on black gram seeds (Dey et al., 2026), cellulose diacetate coatings on soybean increased thickness with coating time while remaining uniform and maintaining ≥90% germination (Durgadevi et al., 2025), and an alginate-based non-fibrous comparison system produced a uniform cross-sectional layer averaging 11 μm (Tritean et al., 2024). In electrospun nutrient coatings, fibre diameter changed from 130 nm before loading to 268–400 nm after loading, indicating that morphology is formulation-sensitive even before seed contact (J et al., 2022).

Adhesion mechanisms are often inferred rather than demonstrated. Mechanical interlocking with ridges, cracks, or depressions is plausible because electrospun mats are porous and can drape onto irregular substrates, but direct proof on seed coats is scarce (Fernando et al., 2023). Broader electrospun-material studies show that wettability, surface functional groups, and surface energy strongly influence nanofibre adhesion: oxygen or amine-rich surface modification can increase adhesion by two- to six-fold, and contact-angle measurements are sensitive indicators of such changes (Janů et al., 2023). Analogously, modified PCL nanofibres become more hydrophilic after collagen coating or TiO_2 incorporation (Ghosal et al., 2016), and cellulose acetate/ZnO seed-coating fibres showed a water contact angle of 131 ± 2°, confirming that hydrophobicity can be deliberately engineered (Zaim et al., 2022). For seed applications, this means wax-rich, low-energy seed coats may require different polymer chemistries from more hydrophilic, polysaccharide- or protein-rich surfaces; SEM, AFM, FTIR, and contact-angle analysis should therefore be treated as essential, not optional, characterization tools (Ghosal et al., 2016; Zaim et al., 2022).

7.2 Water Imbibition, Oxygen Exchange and the Seed–Coating Interface

During germination, the seed–nanofibre interface becomes a dynamic hydrated layer in which water transport, polymer swelling, and gas diffusion occur simultaneously. Direct seed-coating evidence indicates that porous electrospun architectures facilitate rapid water absorption and gas exchange around the seed surface (Dey et al., 2026; Zaim et al., 2022). This is consistent with biological outcomes: black gram seeds carrying nutrient-loaded PVA–PVP nanofibres reached 100% germination within 24 h, whereas controls required about 120 h (Dey et al., 2026), and cellulose acetate nanofibre coatings were also linked to accelerated imbibition through hydroxyl-mediated water uptake (Zaim et al., 2022). In bean and corn germination on electrospun films, water absorption dominated the first 0–48 h, followed by radicle emergence at 48–72 h, matching the time window in which burst release from hydrated fibres is most likely to affect metabolism (An et al., 2025)(Figure 1.3).

However, improved hydration does not guarantee improved germination if oxygen transfer becomes limiting. Indirect but mechanistically relevant hydrogel evidence shows that germination delay arose primarily from restricted oxygen diffusion, not impaired water uptake, and exposing the hilum or micropyle restored germination timing (Phillips et al., 2025). This caveat likely applies to nanofibre coatings as thickness and pore architecture increase. Current seed studies usually demonstrate surface deposition or groove-filling rather than true penetration into internal tissues; claims of internal entry therefore remain unsubstantiated unless shown by cross-sectional microscopy, confocal imaging, fluorescent tracing, or elemental mapping (Dey et al., 2026; Tritean et al., 2024). Better in situ imaging under realistic soil conditions is needed to resolve how the hydrated interface evolves and how that evolution governs water uptake, oxygen availability, active release, and early seedling establishment (Dey et al., 2026; Phillips et al., 2025).

8. CONCLUSION

Electrospun nanofibre seed coatings have emerged as a mechanistically distinct and increasingly well-supported platform for delivering nutrients, phytohormones, biocontrol agents, and plant-growth-promoting microorganisms directly to the seed-soil interface. Across the evidence reviewed, these coatings consistently outperform uncoated seeds and, in several comparisons, conventional film or pelleted coatings, by combining high porosity and surface area with tunable, sustained release. These structural properties translate into faster and more synchronous germination, improved seedling vigour, more efficient nutrient uptake, and enhanced tolerance to drought, salinity, and pathogen pressure, while requiring smaller quantities of active ingredient than conventional treatments. Natural and synthetic polymers each contribute complementary strengths: biocompatibility and functional diversity from natural polymers such as chitosan and alginate, and mechanical integrity and processing reliability from synthetic polymers such as PVA, PVP, and PCL, with blended composite systems increasingly used to reconcile these trade-offs. Polymer concentration, molecular weight, and the interacting solution parameters of viscosity, conductivity, and surface tension remain the principal levers for controlling fibre morphology, and therefore porosity, adhesion, and release behaviour. For microbial delivery specifically, PVA-based aqueous systems have proven particularly effective at preserving viability through processing and storage while permitting hydration-triggered release timed to radicle emergence, with spore-forming bacteria surviving markedly longer than non-sporulating strains after encapsulation. Despite this progress, the evidence base remains uneven: biochemical mechanisms underlying nanofibre-mediated stress tolerance are rarely measured directly, seed-surface adhesion is poorly characterized, and reports connecting laboratory release kinetics to field performance remain scarce. Electrospinning also remains constrained by specialized equipment, formulation-specific optimization, and unresolved questions of scale-up, storage stability, and cost relative to established coating technologies. Nanofibre-based seed coating should therefore be regarded as a promising, functionally superior niche technology for controlled, localized delivery of agricultural inputs, credible but not yet fully validated for widespread field deployment across diverse crops, soils, and environments.

9. Future Thrust

Future research should prioritize direct biochemical characterization, more tightly linking nanofibre-mediated release to reactive oxygen species regulation, antioxidant enzyme activity, osmolyte accumulation, and hormonal signalling during germination, rather than relying solely on inference from non-nanofibre delivery systems. Systematic, comparative field trials across diverse soils, climates, and crop species are needed to validate laboratory-derived germination and yield gains under realistic, variable moisture and temperature conditions. Advanced in situ imaging techniques, including confocal and cross-sectional microscopy, should be used to resolve seed-surface adhesion mechanisms and confirm whether nanofibres remain surface-associated or achieve genuine internal penetration into living seed tissues. Research should also extend microbial encapsulation to fungal biocontrol agents and mycorrhizae, currently absent from the evidence base, and investigate quorum-sensing-mediated rhizosphere establishment more directly. Finally, scale-up of electrospinning, cost reduction, standardized characterization protocols, and long-term storage-stability testing remain essential to move nanofibre seed coatings toward viable, regulator-ready, commercially adoptable agricultural technologies.

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Figures

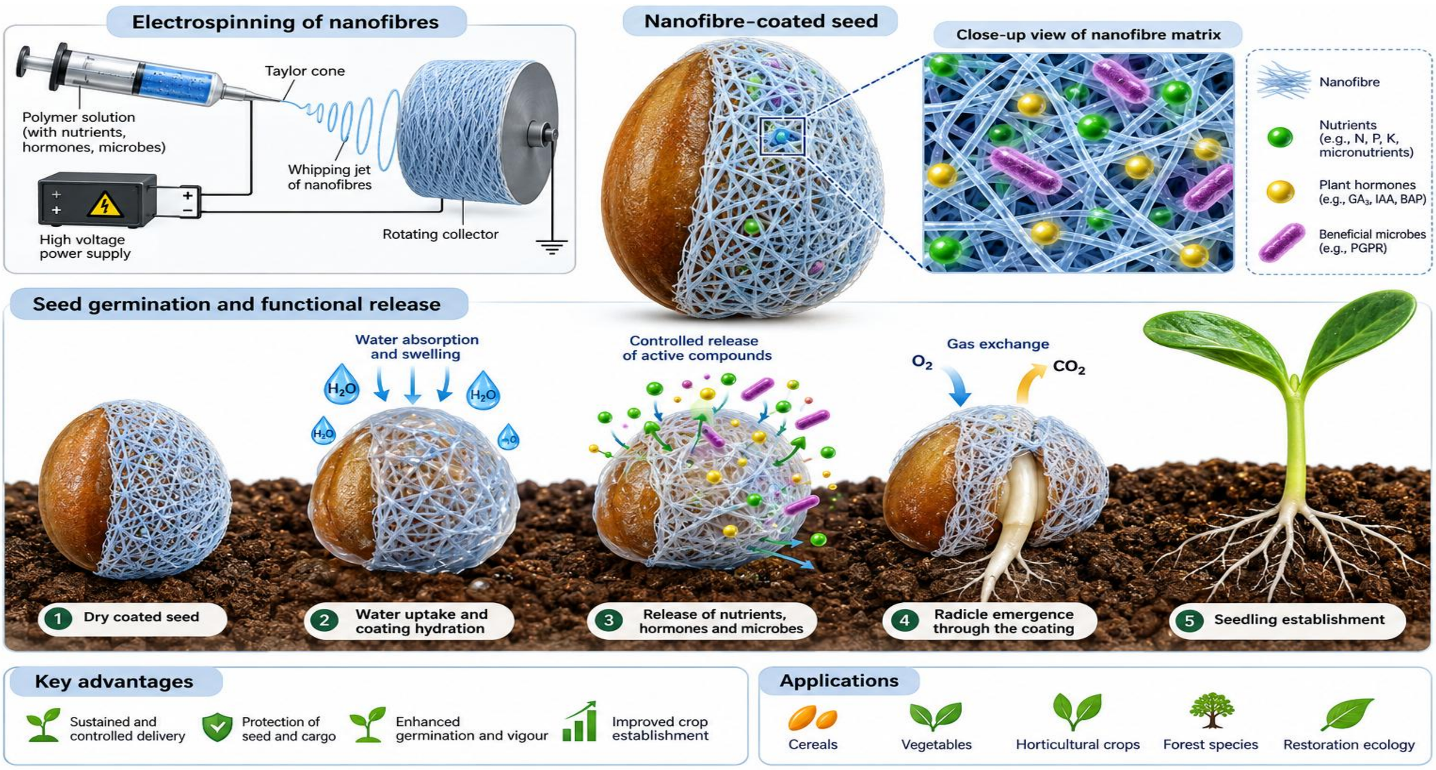

Figure 1.1. Nanofibre seed coating and delivery mechanisms.

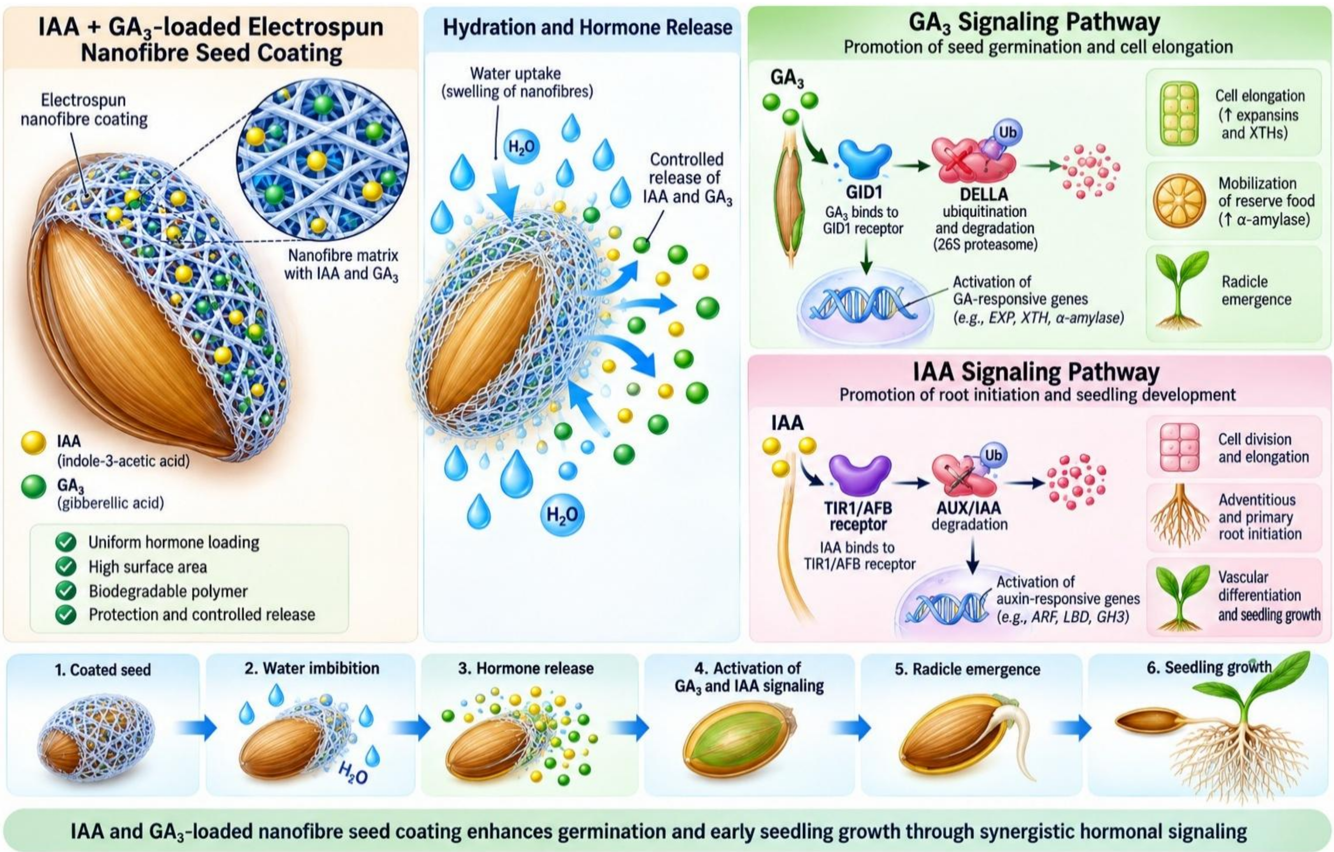

Figure 1.2. GA_3 and IAA signalling pathway

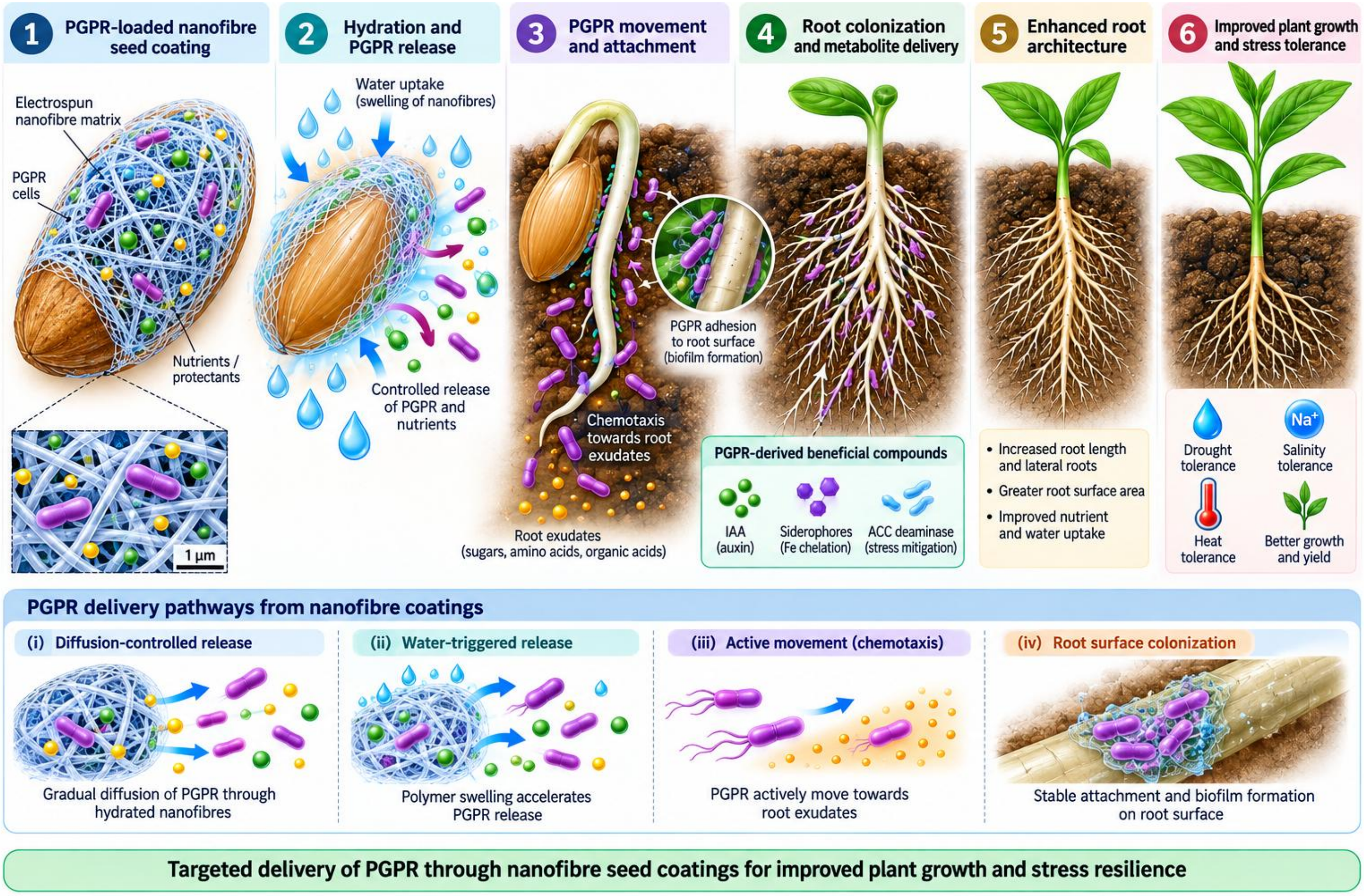

Figure 1.3. Spatiotemporal release of PGPR mitigates abiotic stress by activation of Quorum sensing