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RESEARCH ARTICLE

ADVANCING SUSTAINABLE FORESTRY THROUGH NANOMATERIAL INNOVATIONS

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ABSTRACT

Nanotechnology is an important and rapidly growing area of study and development, where a unique phenomenon offers innovative applications. Nanotechnology around the world is applied in various fields like agriculture, health, environment, forestry etc. In forestry, the technology provides solution to many forest-related problems and it is utilised for improving and protecting wood quality, extinguishing forest fires, successful seed germination, and effective herbal medication delivery. Although nanotechnology has significant potential in the field of forestry as an enabling technology, the future directions and requirements of applying nanotechnology in the forestry sector are still in their infancy, particularly in India. Therefore, present article discusses the basic concept of nanotechnology, innovations and its potential applications in forest. The article also covers deep insights into the techniques of using nanotechnology for disease-resistance, dormancy-breaking seeds, root-enhancers, stress resilience, to develop climate change resilience and pathogen-eradication techniques etc. Development of Bio-Nano-Composites (BNC) also represent a revolutionary frontier in sustainable forestry, offering eco-friendly solutions to enhance forest health, protect timber resources, and improve silvicultural practices.

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INTRODUCTION

Nanotechnology is a leading-edge scientific genre driving advance researches across multiple area (Bayda *et al.*, 2019). By using the unique properties of nano matter, this transformative arena is composed to revolutionize the forestry sector. Current innovations extent varied domains, including reproductive science, water purification, chemical sensors, and the conversion of agricultural waste into energy and valuable by-products via enzymatic nanobioprocessing (Husen and Siddiqi, 2014; Husen and Iqbal, 2019; Husen and Jawaid, 2020). In forestry management, integrating nanomaterials offers innovative solutions for improving wood properties, monitoring environments, and controlling pests. For instance, smart nanopesticides feature targeted, controlled-release mechanisms that maximize pest control efficacy while minimizing ecological collateral damage. Additionally, deploying nanosensors allows for the real-time monitoring of environmental parameters, providing critical data for informed forestry decisions. Beyond protection and monitoring, nanomaterials play a vital role in soil remediation, actively restoring degraded forest ecosystems. Ultimately, nanotechnology represents a major paradigm shift toward sustainable, efficient, and environmentally conscious forestry practices.

As research progresses, gaining a nuanced understanding of how nanomaterials interact within forest ecosystems will be essential to optimize their responsible use and shape the future of the industry.

Nanotechnology in Agriculture and Forestry: The major roles of nanotechnology in these sectors are defined below and sketched in Figures 1 and 2:

- **Eco-Friendly Fertilization:** Nanoparticles (NPs) serve as a promising alternative for manufacturing nano-fertilizers. Compared to conventional options, nano-fertilizers reduce the overapplication of chemical fertilizers, thereby mitigating environmental pollution.
- **Targeted Nano-Formulations:** Agricultural nano-formulations utilize specialized carriers to entrap, encapsulate, absorb, or attach active molecules. This allows for the targeted delivery of specific materials or the activation of precise biochemical processes.
- **Diverse Application Methods:** Nano-fertilizers can be administered through various techniques, including soil application, foliar spraying, seed priming, seedling root dipping, fertilization drip tapes, and aerosol dusting.
- **Enhanced Germination:** NPs facilitate standard seed germination and help break seed dormancy by manipulating the lipids within the cell membrane.

- **Advanced Nano-Priming:** Nano-priming uses nanoparticles to significantly boost seed germination and early growth. This technique enhances overall germination rates while strengthening seed tolerance against both biotic and abiotic stresses.
- **Boosted Photosynthesis:** Nanotechnology improves light absorption in chlorophyll molecules via the plasma resonance effect. By promoting photochemical reactions during the light-capturing phase of photosynthesis, NPs directly increase photosynthetic efficiency.
- **Exactitude Pest Control:** Nano-emulsions blend water and oil phases to create highly effective pesticide formulations for agronomic pest management. For example, polyethylene glycol (PEG) NPs infused with garlic essential oil successfully control the red flour beetle in stored foods. Similarly, porous hollow silica nanoparticles (PHS NPs) loaded with the pesticide validamycin serve as highly effective, controlled-delivery systems.
- **Development of Stress Tolerance:** Nanotechnology introduces Nano-materials that enhance plants genetic, physiological, and biochemical responses against environmental stressors like drought, salinity, and extreme temperatures. These nanomaterials precisely deliver nutrients and target specific cellular pathways to reduce oxidative stress and improve crop resilience. Consequently, this technology provides a sustainable strategy to secure food production amid accelerating global climate changes.
- **Smart Material Delivery:** The engineered properties of nanoparticles allow them to easily penetrate or be absorbed by plant cells, significantly enhancing nutrient uptake. This targeted conveyance ensures efficient nutrient management, lowers environmental stress, and drives crop productivity.
- **Constant Nutrient Release:** Nanoparticles facilitate controlled-release mechanisms that ensure a gradual, sustained supply of nutrients over extended periods. This synchronizes nutrient availability with plant demand, reducing wastage and protecting delicate soil biota.
- **Natural Sensing:** Nano-biosensors efficiently convert biological responses into readable electrical signals, making them a highly promising technology for real-time sensing and detection.
- **Forestry Optimization:** In forestry, nanotechnology improves the detection and treatment of tree diseases, resulting in healthier forests and higher timber yields. Additionally, it aids in manufacturing advanced, high-performance wood-based materials.

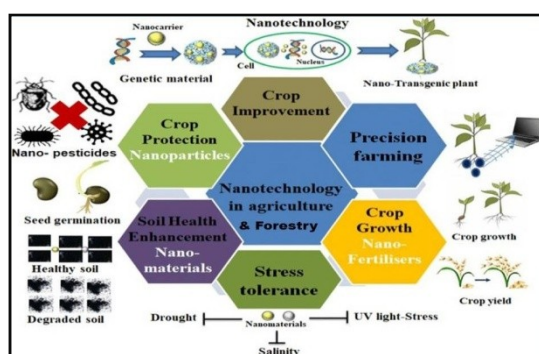


Figure 1. Major role of Nanotechnology

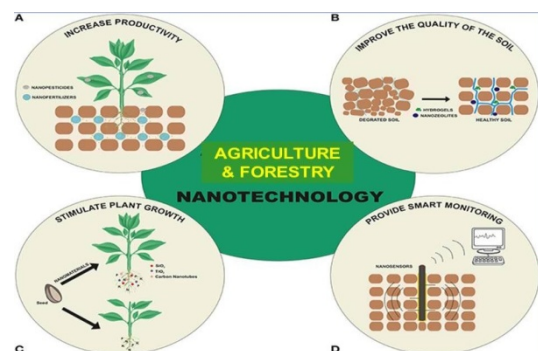


Figure 2. Major role of Nanotechnology

Nano Material

Definition and Core Properties of Nanomaterials:

Nanomaterials are substances characterized by having at least one external dimension or internal structure scaled between 1 and 100 nanometers (nm). To put this scale into perspective, a single nanometer is one-billionth of a meter—approximately 100,000 times smaller than the width of a human hair. At this microscopic scale, materials transition into a distinct state of matter, exhibiting physical, chemical, and biological behaviors vastly different from their larger, bulk counterparts. Researchers highly favor nanomaterials due to these unique, scale-dependent features, which include specialized pore sizes, reactive surface groups, and an exceptionally high surface-area-to-volume ratio (Mukhopadhyay, 2014).

Applications in Plant and Agricultural Sciences: Because of these distinctive traits, nanomaterials have secured an active, essential role in agricultural applications (Kaphle *et al.*, 2018). Specifically, advancements in the field of phyto-nanotechnology are gaining significant academic attention regarding its innovative processes, products, and practical operations (Arruda *et al.*, 2015; Kumaraswamy *et al.*, 2018 a,b). To date, various specialized biomaterials have been synthesized, characterized, and deployed within plant sciences. These nanomaterials serve critical functions, such as facilitating the controlled release of micronutrients, acting as antimicrobial agents, and building crop tolerance against both biotic and abiotic stresses. Depending on the objective, these engineered nanomaterials or biocomposites can be applied independently or combined with compatible polymers (Mai & Yu, 2006).

Nano Fertilizer: Consequently, the application of nano-fertilizers offers an innovative, highly efficient, and eco-friendly alternative to traditional fertilizers (Kalia *et al.*, 2020; Kalwani *et al.*, 2021; Upadhyay *et al.*, 2023). These specialized formulations play a critical role in agricultural productivity by boosting crop growth, total yield, and various quality parameters across diverse plant species (Tarafder *et al.*, 2020; Nongbet *et al.*, 2022). Furthermore, nano-fertilizers strengthen plant tolerance mechanisms against both biotic and abiotic stresses (Seleiman *et al.*, 2021; Verma *et al.*, 2022). Serving as a slow-release nutrient delivery system, they significantly improve overall nutrient use efficiency (Yadav *et al.*, 2023). By minimizing fertilizer runoff and waste, this technology reduces adverse environmental impacts while simultaneously lowering total cultivation costs (Kumar *et al.*, 2021; do Couto Junior MC *et al.*, 2025; Iduary and Biswas, 2025). Application of Nano Fertilizer: Major role of nano-fertilizer on plant and soil are illustrated in Figure 3:

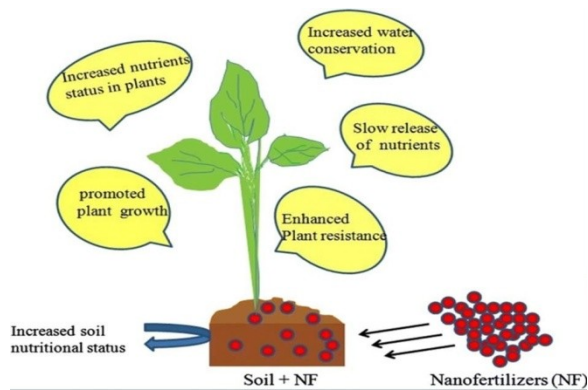


Figure 3. Major role of nano-fertilizer on plant and soil Classification, Mechanisms, and Research Gaps in Nano-Fertilizers:

Nano-fertilizers represent highly engineered agricultural inputs wherein plant nutrients are encapsulated within nanomaterials (Iqbal, 2019; Tayade *et al.*, 2022). These formulations can be administered directly through soil applications or as foliar sprays (Mejias *et al.*, 2021). Generally, nano-fertilizers are categorized into three primary classes: nanoscale fertilizers containing actual nutrients, conventional fertilizers enhanced with nanoscale extracts, and conventional fertilizers featuring nanoscale coatings (Mikkelsen, 2018). Due to their high surface-area-to-volume ratio, nano-fertilizers facilitate a slow, steady, and efficient uptake of nutrients by plants (Dhlamini *et al.*, 2020; Tarafder *et al.*, 2020). Consequently, Jain *et al.* (2021) characterized them as "smart delivery systems" due to their superior absorption capacities and controlled-release kinetics. In modern agriculture, nanoparticles (NPs) are predominantly utilized for nutrient management, plant growth promotion, pest control, and food processing enhancements (Mir *et al.*, 2023). Within nano-fertilizers, these particles serve as specialized carriers for both micronutrients (such as zinc, copper, manganese, and iron) and macronutrients (including nitrogen, phosphorus, potassium, sulfur, and calcium) (Divekar *et al.*, 2021). However, the broader economic and marketing dynamics of nano-fertilizers require more extensive investigation (Azmi and Elgharbawy, 2024).

Recent investigations have dedicated significant attention to the agronomic impacts of nano-fertilizers (Ayenew *et al.*, 2024; Reddy *et al.*, 2024; Saurabh *et al.*, 2024; Iduary and Biswas, 2025). Nonetheless, these studies have often failed to comprehensively scrutinize critical parameters. Specifically, there is a lack of deep analysis regarding their application across diverse crop categories—such as vegetables, field crops, fruits, and spices—as well as the precise mechanisms governing their cellular uptake and plant interactions. Furthermore, existing literature frequently overlooks direct comparisons between nano-fertilizers and their conventional counterparts, particularly regarding greenhouse gas emissions and broader climate change implications. Our research directly addresses these critical gaps, establishing a comprehensive database designed to benefit diverse agricultural stakeholders.

Nano-fertiliser and its interaction with plants: To accurately evaluate the positive impacts of nano-fertilizers, it is essential to understand the underlying physiological and biochemical responses of plants (Padhan *et al.*, 2023). When interacting with nanoparticles, plants undergo various morphological and physiological alterations that depend heavily on the specific properties of the nanoparticles themselves (Yadav *et al.*,

2023). On foliar surfaces, the presence of stomata and nanopores facilitates the initial uptake and deep penetration of nano-fertilizers into the leaves, resulting in superior nutrient use efficiency (Iqbal, 2019; Desai *et al.*, 2022). Furthermore, because the pores within the plant cell wall diameter (typically ranging from 5 to 20 nm) are larger than the diameter of engineered nanoparticles, these materials easily pass through the cell wall barrier to reach the plasma membrane (Sultana *et al.*, 2021). Overall, nutrient absorption, translocation, and accumulation are directly governed by the shape, size, molecular structure, stability, and surface functionalization of the nano-fertilizer (Mushtaq *et al.*, 2020).

When applied to the rhizosphere, encapsulating nutrients within nano-carriers mitigates leaching and infiltration losses by keeping the nutrients localized in the soil around the root zone. At this interface, the nanomaterials interact with the soil matrix through hydrogen bonding, molecular forces, surface tension, or viscous forces (Bernela *et al.*, 2021). The explicit pathways of nanoparticle uptake and internal translocation have been verified using transmission electron microscopy (Abdel-Aziz *et al.*, 2016; Iduary and Biswas, 2025). Due to their minuscule size, nano-fertilizers undergo highly efficient absorption by plant roots. Once inside, they are transported via apoplastic and symplastic pathways into the xylem and vascular bundles, through which they are distributed to various distant organs of the plant (Mahanta *et al.*, 2019).

Advantages of nano-fertiliser over conventional fertiliser:

The application of conventional fertilizers significantly destabilizes soil nutrient retention, causing substantial losses through leaching, volatilization, and surface runoff, which ultimately degrades fertilizer efficiency (Shang *et al.*, 2019; Maity *et al.*, 2024). In contrast, nano-fertilizers are engineered to serve as highly effective alternatives, exhibiting distinct physical and chemical properties compared to their bulk counterparts (Al-Tameemi *et al.*, 2019). Because they experience minimal environmental loss, nano-fertilizers remain sustainable even when applied in significantly lower quantities, whereas synthetic fertilizers must be applied in massive volumes to offset heavy leaching and emission losses (Iqbal, 2019; Salcido-Martinez *et al.*, 2020; Mahapatra *et al.*, 2022).

This superior efficiency is driven by the unique physical attributes of nanomaterials. Specifically, their higher surface area increases available reactive sites, which directly enhances nutrient absorption in plants (Sadak and Bakry, 2020). Additionally, the higher surface tension of nanomaterials allows them to bind and hold nutrient molecules far more securely than conventional substrate surfaces (Easwaran *et al.*, 2024), while their minuscule size improves both dissolution rates and overall nutrient use efficiency (Kanjana, 2020; Sahar *et al.*, 2020). Consequently, while chemical fertilizers release their nutrients rapidly within 4 to 10 days, nano-fertilizers feature a controlled release spanning 40 to 50 days (Seleiman *et al.*, 2021). By delivering nutrients slowly over an extended period, nano-fertilizers safeguard the environment (Wangdi, 2019) and mitigate negative ecological footprints (Okey-Onyesolu *et al.*, 2021). Furthermore, nano-formulated micronutrients prevent soil adsorption and chemical fixation, thereby enhancing nutrient bioavailability (Ojeda-Barrios *et al.*, 2020). Conversely, conventional fertilizer nutrients suffer from low solubility due to their large particle sizes and high rates of soil particle fixation (Mushtaq *et al.*, 2020).

Over the past decade, nano-fertilizers have routinely outperformed even the most innovative polymer-coated conventional fertilizers (DeRosa *et al.*, 2010). Without altering their core chemical formulations, nano-fertilizers maintain high stability in the soil matrix by optimizing aggregation behaviors, redox potentials, and ligand accessibility (Bratovic *et al.*, 2021). Finally, nano-fertilizers are recognized as economically viable substitutes because their extended shelf life reduces transportation and field application costs (Al-Hchami and Alrawi, 2020), while their low-toxicity profiles render them safer for both human health and surrounding ecosystems (Nongbet *et al.*, 2022; Iduary and Biswas, 2025). Although nano-fertilizers carry high manufacturing costs, their superior efficiency significantly lowers their required application rates. For example, while a 1-hectare area typically requires up to 200 kg of conventional fertilizer, the same crop yield can be achieved using only 40 kg of nano-fertilizer (Su *et al.*, 2022). This drastic reduction directly translates into lower input costs for farmers; notably, a single 500 mL bottle of nano-urea delivers an agronomic effect equivalent to a traditional 45 kg bag of conventional urea.

In addition to synthetic variants, biological nano-fertilizers—commonly termed nano-biofertilizers—represent a major technological advancement. Developed by integrating nano-biotechnology, these formulations combine nanoscale (1–100 nm) organic fertilizers with living microorganisms or wrap biofertilizers within specialized nanomaterial coatings (Sood, 2021). Nano-biofertilizers serve as novel, cost-effective, and environmentally friendly inputs that simultaneously leverage the beneficial properties of both nanomaterials and biological inoculants (Kumari and Singh, 2020). Furthermore, composite nano-fertilizers are engineered by blending two or more distinct nanomaterials or nanostructures to yield a specialized formulation with enhanced capabilities and performance. The continuous advancement of nanocomposite fertilizer technology offers a powerful framework to mitigate critical agricultural challenges, such as chronic nutrient leaching and low crop yields (Easwaran *et al.*, 2024).

Use of nano-fertiliser is Eco-Friendly: Agro-ecosystems significantly contribute to global warming through the emission of greenhouse gases (GHGs). Conventional agricultural methods and traditional inputs like prilled urea release substantial volumes of potent GHGs, specifically methane (CH_4) and nitrous oxide (N_2O). Consequently, nano-fertilizers are gaining widespread popularity in field applications due to their ability to simultaneously reduce GHG emissions and enhance crop productivity (Sun *et al.*, 2024). Because of their nanoscale dimensions, these fertilizers regulate the release and availability of nutrients—particularly nitrogen—which is critical for suppressing CH_4 and N_2O emissions (Babu *et al.*, 2024).

Nano-fertiliser enhances plant growth: Nano-fertilizers significantly optimize plant development and yield across diverse crop types. By improving nutrient use efficiency and curbing environmental runoff, this technology offers an economically viable and ecologically sound alternative to conventional fertilizers, thereby minimizing severe ecological threats like eutrophication and water pollution. Furthermore, nano-fertilizers enhance plant stress tolerance, reduce agro-ecosystem degradation, and facilitate controlled nutrient release over extended periods. Statistically, this technology prevents massive nutrient losses, saving approximately 40–

70% of nitrogen, 80–90% of phosphorus, 50–70% of potassium, and over 95% of applied micronutrients. Whereas synthetic chemical fertilizers degrade soil fertility, long-term productivity, and water quality, nano-fertilizers exert a profoundly positive impact on sustainable crop production. Accordingly, this article emphasizes the critical advantages of nano-fertilizers, including enhanced nutrient uptake, minimized fertilizer waste, and mitigated environmental degradation. Nanotechnology tools and techniques represent a vital alternative framework for the future of global agriculture. Their minuscule particle size enables efficient penetration through leaf cuticles for targeted internal delivery. However, rigorous care must be exercised during selection and field deployment, as the precise physiological effects of nano-fertilizers vary according to plant type and are strongly dictated by nanoparticle shape, size, and application methodology (Iduary and Biswas, 2025).

Chitosan and Chitosan Based Nano Composites: Chitosan is the deacetylated derivative of chitin (Fig. 4), ranking as the second most abundant natural biopolymer on Earth after cellulose (Kaya *et al.*, 2014; Riseh *et al.*, 2026). Chemically, this polysaccharide is composed of repeating glucosamine and N-acetyl-glucosamine residues (Sashiwa & Aiba, 2004). Within the biosphere, approximately 100 billion tons of chitin is produced annually by living organisms. Consequently, both chitin and chitosan serve as highly economical polymers, as they can be easily isolated from diverse biological and marine waste streams. These sources include the exoskeletons of crustaceans (such as crabs and shrimp), various arthropods, and fungal microorganisms.

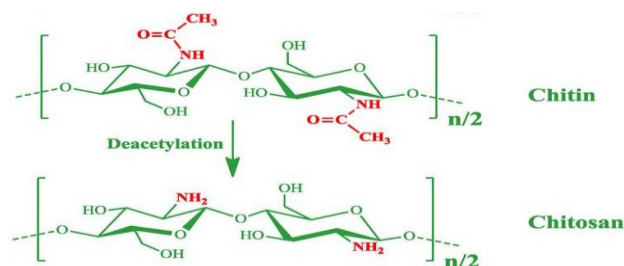


Figure 4: Structure of Chitin and Chitosan

Remarkably, chitin remains largely underutilized despite representing a massive, renewable biomass resource (Medeiros *et al.*, 2010). Compared to chitin, its deacetylated derivative, chitosan, exhibits an exceptional complex-forming ability primarily driven by the abundance of free amino (NH_2) groups distributed along its backbone (Medeiros *et al.*, 2010). Consequently, this polysaccharide is recognized as an extraordinarily versatile and promising biopolymer. Due to its distinctive physicochemical properties, along with its inherent antiseptic, wound-healing, and immune-stimulating activities, chitosan possesses a significantly higher functional potential across various industries than even cellulose (Medeiros *et al.*, 2010; Riseh *et al.*, 2026). Structurally, the chitosan macromolecule consists primarily of $\beta(1 \rightarrow 4)$ linked D-glucosamine residues (Fig. 4). Its fundamental uniqueness lies in the fact that it is the only naturally occurring cationic polysaccharide. Because the surfaces of most engineered nanomaterials carry a negative charge, bionanocomposites can be readily constructed via electrostatic self-assembly between these oppositely charged counterparts. Thus, chitosan holds immense promise as a foundational building block for advanced bionanocomposites. However, while mixing these components appears straightforward in theory, practical

execution remains highly challenging. Chitosan is exceptionally sensitive to the presence of anionic substances within its solutions; even trace amounts of negative ions trigger rapid aggregation and the formation of a highly heterogeneous precipitate (Medeiros *et al.*, 2010). The surprising thing is that chitin is still almost unutilized in spite of the huge renewal resource of biomass (Medeiros *et al.* 2010). Compared to chitin, chitosan has an excellent complex-forming ability, that can be mainly ascribed to the availability of free $-NH_2$ groups distributed along the main chain of the chitosan (Medeiros *et al.* 2010). It is also agreed that this polysaccharide is an extraordinary underexploited biopolymer of significant versatility and promise, having a much higher potential for applications in many fields owing to its distinctive physico-chemical properties and antiseptic, wound-healing, and immune-stimulating activities (Medeiros *et al.* 210; Rishch *et al.* 2026). The whole range of mentioned advantages is even superior to that of the cellulose. Chitosan macromolecule consists primarily of $\beta(1 \rightarrow 4)$ linked D-glucosamine residues (Fig. 4). It is the only cationic polysaccharide, and therein lies its uniqueness. The surface of most nanoscale materials is negatively charged. Therefore, bionanocomposite construction can be performed via electrostatic interactions of oppositely charged counterparts. Chitosan has a great potential as a building block for making bio-nano-composites. It seems to be a simple matter to mix them together but in actual practice it is not so easily realizable. Chitosan is very sensitive to the presence of anionic substances in its solutions (Medeiros *et al.* 2010). Even their trace amount brings about the formation of a heterogeneous precipitate of aggregated counterparts.

Production Method of Chitosan: Chitosan is a biopolymer containing D-glucosamine units linked through $(\beta-1 \rightarrow 4)$ glycosidic bonds. Some glucosamine units in the chitosan structure are acetylated. Due to the chemical structure of chitosan, unlike most other biopolymers, this biopolymer is only soluble in dilute acid solutions. In order to extract and purify chitin from crustacean wastes, the wastes are decalcified, deproteinized, and decolorized. To prepare chitosan from chitin, part of the acetyl groups must be separated from the polymer structure. For deacetylation, chemical and enzymatic methods can be used (Fig. 5) (Yang *et al.* 2023).

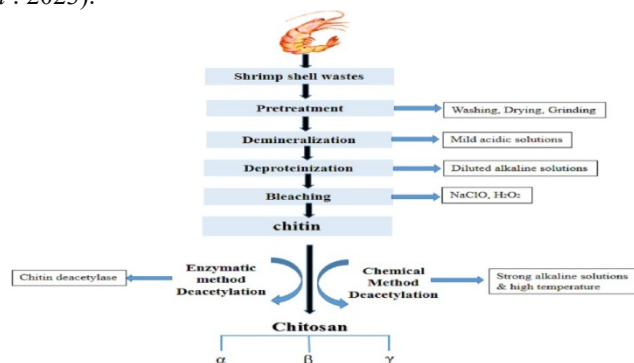


Fig.5 Preparation of chitin and chitosan from shrimp shell wastes(Yang *et al.* 2023)

A defining peculiarity of chitosan is its behavior as a weak polyelectrolyte, meaning its surface charge density is strictly dependent on the solution pH (Rishch *et al.*, 2026). By systematically adjusting the acidity or alkalinity, researchers can seamlessly transition chitosan between charged and uncharged states in an aqueous solution.

This specific property was recently leveraged by our team to regulate its electrostatic

interactions with anionic substances and nanoparticles, thereby optimizing the self-assembly of bio-nanocomposites (Medeiros *et al.*, 2010). When deployed in agriculture and forestry, this multi-benefit, signaling macromaterial functions across several critical domains:

- **Pathogen Suppression:** Exhibiting potent antimicrobial activities against a broad spectrum of fungal, bacterial, and viral plant pathogens.
 - **Post-Harvest Preservation:** Serving as an effective, biodegradable fruit preservative coat.
 - **Precision Agro-Chemical Delivery:** Acting as a smart matrix for the controlled and sustained release of pesticides, insecticides, and fertilizers.
 - **Growth Promotion:** Increasing endogenous auxin concentrations, boosting seed germination capacity, extending root length and cellular activity, and enhancing overall seedling height and diameter.
- Application of Chitosan in Agriculture and Forestry: Major applications are as following:
- Antimicrobial activities against various plant pathogens.
 - Fruit preservative.
 - For controlled delivery of fertilizers,
 - As pesticides and insecticides.
 - To Increase in the auxin concentration and urea release in the soil, germination capacity, root length and activity, and seedling height and dia.

By inducing innate plant immune responses, chitosan significantly boosts seedling vigor and crop establishment across diverse plant species (Katiyar *et al.*, 2015). Under acute salinity stress, chitosan applications have been shown to increase shoot length, root length, shoot dry weight, and relative water content. It mitigates osmotic stress by adjusting cellular osmotic pressure, which enhances the availability and root uptake of water and essential elements (Guo *et al.*, 2022). Furthermore, it directly optimizes plant nutrition by improving soil fertility metrics, facilitating nitrogen fixation, and increasing overall mineral assimilation (Dzung *et al.*, 2011; Van *et al.*, 2015). Engineered nanocomposites are specifically developed to overcome the limitations of single-matrix materials by significantly improving their physical, chemical, and biological properties, thereby widening their commercial applicability (Esumi *et al.*, 2003; Huang *et al.*, 2004). Historically, metal-based nanomaterials were heavily utilized in plant sciences (Kaur *et al.*, 2015; Salam *et al.*, 2011). However, emerging concerns regarding potential phytotoxicity have compelled researchers to rigorously investigate the threshold levels of heavy-metal toxicity in agronomic applications (Wang *et al.*, 2015; Young & Santra, 2014; Rishch *et al.*, 2026). Over the past two decades, this has driven a major shift toward examining biogenic polymers as safe, highly compatible alternatives.

Chitosan-Based Bio-nanocomposites: Advantages and Synthesis. Among various biopolymers—including chitin, cellulose, starch, and gelatin—chitosan has garnered widespread attention. It is highly valued for its biodegradability, biocompatibility, non-toxicity, plant-growth regulatory traits, and stress-inhibitory profiles (Malerba &

Cerana, 2018; Mujtaba *et al.*, 2019; Yu *et al.*, 2021; Riseh *et al.*, 2026). Isolated economically from marine waste, insects, and fungi (Koide, 1998), chitosan displays structural instability in media with fluctuating pH or variable ionic strength due to its cationic nature. Nevertheless, its chemical structure possesses abundant functional groups that enable it to react easily with other active compounds (Yu *et al.*, 2021; Riseh *et al.*, 2026). This makes it highly maneuverable without compromising its inherent antimicrobial and elicitor profiles, outperforming neutral or anionic biopolymers like starch and glucans (Yin *et al.*, 2016). To enhance its biological performance, chitosan-based nanomaterials are deployed as nanoparticles, microbeads, or microfibrils (Sathiyabama and Parthasarathy, 2016; Zargar *et al.*, 2015). Integrating chitosan with nanometals—such as iron (Fe), copper (Cu), silver (Ag), silicon (Si), zinc (Zn), zinc oxide (ZnO), and titanium dioxide (TiO₂) significantly amplifies its antimicrobial properties (Yu *et al.*, 2021). Furthermore, incorporating active botanical extracts or essential oils into the polymer matrix further optimizes its bioactivity. Depending on the target architecture, these chitosan-based nanocomposites and bio-nanocomposites (Ch-NCs / Ch-BNCs) can be synthesized using diverse techniques, including emulsion droplet coalescence or the reverse micellar method (Mitra *et al.*, 2001), ionic gelation (Calvo *et al.*, 1997), precipitation (Agnihotri *et al.*, 2004), or sieving and spray drying (He *et al.*, 1999) (Fig. 3). All the above-described techniques follow the bottom-up approaches where all the ions and molecules are assembled into the nanostructure. The synthesis of Ch-NCs can be influenced by various factors, but maintaining the desired physicochemical traits during the synthesis is a difficult task (Chan & Kwok, 2011). The production protocols of nanocomposites are still under research and researchers are trying to optimize the protocols for obtaining the Ch-NCs / Ch-BNCs with higher efficiency (Riseh *et al.* 2026; Yu *et al.* ,2021). Microbial Synthesis of Chitosan based Bio-Nano Composite and its application are presented in Figure 6.

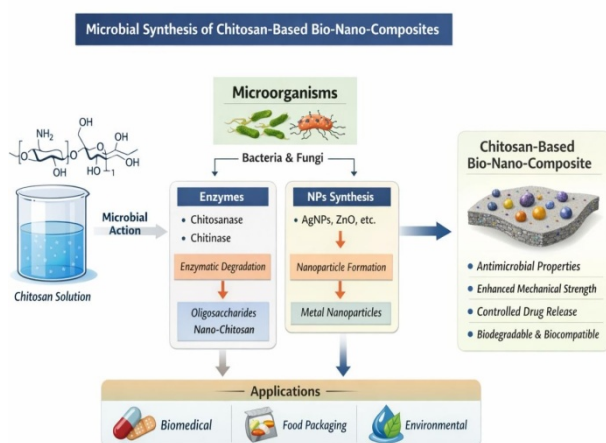


Figure 6. Microbial Synthesis of Chitosan based Bio-Nano Composite and its application

The currently available agrochemicals that are applied to seeds, soil, or through the foliar spray, cannot reach directly to plant cells. But, the Ch-NCs have been specifically designed to reach or imbibe to the internal tissues and organs in plants due to their nano-size. Narrow-sized nanocomposites can easily pass through the plant's surface and produce collective effects compared to bigger or broad-sized nanocomposites (Riseh *et al.* 2026).

Chitosan-based nanocomposites (ChNCs) applications in plants:

Anti-fungal activity of ChNCs: Fungal pathogens are among the most destructive threats to agricultural and forest commodities worldwide (Rossman, 2008). By producing toxic mycotoxins, they cause significant pre-and post-harvest damage to fruits, grains, and other essential foods. Approximately 300 fungal metabolites have been identified as toxic to humans and animals (Nesic *et al.*, 2014). Biopolymers such as chitin, chitosan, cellulose, and alginate have been widely evaluated across various crops as sustainable alternatives. Among these biopolymers, chitosan has garnered widespread scientific interest due to its exceptional physicochemical properties and potent, inherent antifungal activity. The precise efficacy of chitosan against fungi is governed by several interactive physicochemical factors, including its degree of deacetylation, molecular weight, solution pH, and biological source. Empirical studies demonstrate that chitosan successfully inhibits fungal progression across multiple growth stages, including mycelial elongation, sporulation, spore viability, germination, and the synthesis of fungal virulence factors. Furthermore, chitosan can be deployed either as a standalone agent or complexed with other elements—particularly metal nanoparticles—to amplify its antifungal effects (Poznański *et al.*, 2023).

Anti-bacterial activity of ChNCs/ Ch BNCs: Over the past few decades, chitosan has emerged as a potent antibacterial agent, a characteristic primarily attributed to its polycationic nature. Chitosan-based nanocomposites and bionanocomposites (Ch-NCs / Ch-BNCs) exhibit broad-spectrum antimicrobial activity against both Gram-positive and Gram-negative bacteria (Wang *et al.*, 2024). This inhibitory efficacy is influenced by multiple intrinsic and extrinsic factors, including molecular weight, degree of deacetylation, concentration, and the specific type of acidic solvent utilized (Liao, *et al.*, 2024). While the exact molecular mechanism remains the subject of ongoing research, several prominent hypotheses explain its antimicrobial mode of action through both direct and indirect pathways. For Example the physical deposition of chitosan on the cell surface forms a restrictive layer that blocks nutrient uptake and prevents the transport of metabolic wastes. Indirect way is through strengthening host plant defence systems at the cellular level (Youssef *et al.*, 2020; Wang *et al.*, 2023; Liao, *et al.*, 2024; Yuan and Chen, 2024).

Application in Disease Management: Ch-NCs and Ch-BNCs are widely applied to eradicate and prevent devastating diseases across various crops. Upon binding to cell membranes, these chitosan-based nanoformulations activate multiple signaling pathways responsible for synthesizing crucial defense-related enzymes and proteins, including phenylalanine ammonia-lyase (PAL), polyphenol oxidase (PPO), peroxidase (POX), catalase (CAT), superoxide dismutase (SOD), and various PR proteins (Sathiyabama and Charles, 2022; Malerba and Cerana, 2023; Liao, *et al.*, 2024).

Anti-viral activity of Ch-NCs

Antiviral Efficacy and Differential Host Responsiveness: To date, only a limited number of studies have explored the applications of chitosan-based nanomaterials in plant virology, leaving the precise antiviral mechanisms of chitosan-based

nanocomposites (Ch-NCs) somewhat uncertain (Abdelkhalek *et al.*, 2023).

In Plant nutrient uptake: Agrochemicals, including macronutrients and fertilizers, are vital inputs for optimizing plant development, boosting yield potential, and inducing resistance against diverse biotic and abiotic stresses. However, the incessant and unmanaged application of these conventional agrochemicals triggers severe ecological and economic drawbacks. Over 90% of traditionally applied agrochemicals are lost to the atmosphere or washed away via surface runoff into surrounding water bodies and soils. This massive inefficiency directly undermines the economic sustainability of modern agriculture and inflicts a profound negative impact on the global environment. Biogenic nanomaterials offer immense promise in agriculture, effectively solving field-level issues by facilitating the slow, controlled release of encapsulated nutrients, fertilizers, and pesticides and improve nutrient uptake (Bhatt *et al.*, 2024; Malerba and Cerana, 2025).

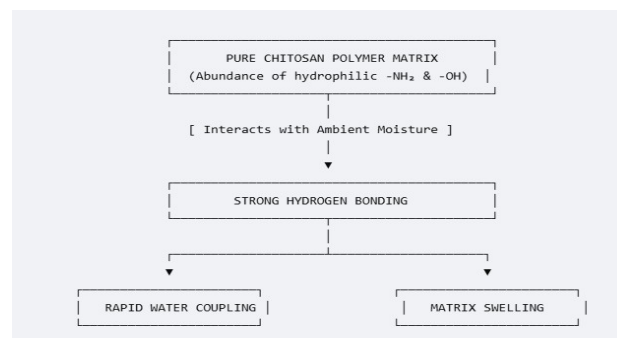
Effect of Ch-BNCs on plant's seedling and growth The target-site delivery of biologically active nanoformulations represents a critical research advancement for optimizing modern agricultural practices and meeting global food demands. This intervention directly addresses the chronic over application of agrochemicals, such as conventional fertilizers and pesticides, which frequently suffer from reduced bioavailability due to environmental runoff and soil chelation (Bhatt *et al.*, 2024). Consequently, a major trend in crop improvement programs involves using micronutrient-enriched nanomaterials—such as nano-chitosan encapsulated formulations—to facilitate the controlled, gradual, and stable release of fertilizers, biofertilizers, pesticides, biopesticides, and phytohormones. Functioning as smart delivery systems, these engineered matrices provide a sufficient, sustained supply of essential nutrients over extended periods while minimizing ecological harm. Polymeric-based encapsulation strategies routinely utilize biocompatible polymers like chitosan, chitin, and cellulose to construct diverse nano-delivery systems aimed at maximizing plant nutrient uptake. Beyond nutrient delivery, these formulations actively enhance early plant development; for example, chitosan nanoparticles (NPs) have demonstrated highly positive effects on germination percentages, resulting in a significantly higher seedling vigor index and increased vegetative biomass in crops such as chickpeas (Sathiyabama & Parthasarathy, 2016). However the applications of chitosan-based nanomaterials in forestry is very limited.

In Increase of defence Mechanism: The application of Chitosan-based Bionanocomposites (Ch-BNCs) acts as a powerful elicitor that triggers and elevates a plant's innate immunity. Due to their nanoscale size and synergistic blend matrices, Ch-BNCs are highly efficient at inducing Systemic Acquired Resistance (SAR). They boost metabolic pathways to protect crops against pathogenic fungi, bacteria, and harsh environmental stress. As biostimulants, chitosan nanoformulations promote robust vegetative growth and development while simultaneously enhancing disease suppression by activating multiple defense pathways, including induced systemic resistance (Malerba and Cerana, 2023).

Chitosan as a Matrix for Controlled-Release Fertilizers: While conventional agrochemicals are essential for high-

quality crop production, they are increasingly recognized as severe agricultural pollutants. Driven by shifting consumer patterns and a growing global population, the relentless overapplication of traditional fertilizers degrades biodiversity, transforms natural habitats into hyper-intensive agricultural arrangements, and discharges heavy volumes of chemical pollutants and greenhouse gases. To establish eco-friendly and sustainable agricultural options, numerous studies have focused on achieving uniform, sustained nutrient distribution. By leveraging rapidly evolving smart nanomaterials and naturally occurring, degradable biopolymers, researchers aim to develop efficient Controlled-Release Fertilizers (CRFs). Although using chitosan as a foundational matrix for CRFs is still in its primary stages, it represents an excellent fertilizer candidate. This potential is underpinned by its inherent biodegradability, eco-friendly footprint, and a highly porous surface microstructure that actively facilitates water retention and root nutrient uptake (Kalia *et al.*, 2020; Sreelakshmi *et al.*, 2024).

Chitosan for Advanced Seed Treatments: Deploying chitosan as a seed film-coating delivery system establishes a highly effective physical barrier against insect pests and phytopathogens. This seed-priming technique significantly enhances the seed germination index and shortens both the mean germination time and overall flowering time, while accelerating vegetative growth and biomass accumulation. This observed developmental boost is partially linked to the incorporation of essential nutrients from the polymer matrix, particularly nitrogen. Furthermore, applying chitosan coatings to wheat seeds against *Fusarium graminearum* infections significantly elevates total phenolic content and increases the activity of defense-related enzymes and antioxidants, culminating in enhanced crop growth and heightened resistance against the target pathogen (Sreelakshmi *et al.*, 2024).



Chitosan in Moisture Absorption: Chitosan serves as a powerful hydro-retaining agent in agriculture by forming highly porous networks that mechanically entrap liquids and biochemically shield crops against drought stress (Yang *et al.*, 2023; Shinde *et al.*, 2024). Chitosan-based nanocomposites naturally possess a highly hygroscopic character, a property directly driven by the abundance of hydrophilic amine (-NH₂) and hydroxyl (-OH) functional groups distributed along the polymer matrix backbone (Figure 7). These highly active functional groups readily establish strong hydrogen bonds with ambient moisture, causing pure chitosan films to undergo rapid water absorption and subsequent swelling. While this pronounced hygroscopicity is exceptionally advantageous for agricultural applications demanding maximum moisture retention, it presents severe engineering challenges for moisture-sensitive sectors—such as biodegradable food packaging—where water-barrier resistance is critical (Chandra

et al., 2023; Yalcin and Cankaya, 2022; Sreelakshmi et al., 2024). This property may be proven very important, since most of the plantations are done under rainfed conditions. Figure 7: Hygroscopic nature of Chitosan based Bio Nano Composite

Formulation Bio-Nano-Composite (BNC) with Microbial Fertilizers: Formulating a Bio-Nano-Composite (BNC) through the direct incubation of chitosan with a microbial consortia utilizes the polymer's active functional groups to act as a biocompatible anchoring matrix. Unlike ionic encapsulation, this incubation method relies on self-assembly: the living microbial cells naturally adhere to the chitosan chains while the added nanoparticles organize into a protective, structured barrier. Microbes also releases lyase enzymes which breaks the Chitosan to small molecules which in combinations with different biomolecules released by Microbes forms Bio Nano Composites (Figure 8).



Figure 8. Formulation of Bio-Nano-Composite (BNC) with Microbia Fertilizers

Role of Chitosan-based bio-nanocomposites in Forestry: Role of Chitosan-based bio-nanocomposites are not much studied in case of Forestry. Here similar effects in agriculture have been discussed. Chitosan-based bio-nanocomposites represent a revolutionary frontier in sustainable forestry, offering eco-friendly solutions to enhance forest health, protect timber resources, and improve silvicultural practices. Derived from the chemical deacetylation of chitin—the second most abundant natural polymer globally—chitosan possesses intrinsic biocompatibility, biodegradability, non-toxicity, and antimicrobial properties. (Azmana et al , 2021; Kumar et al , 2025; Sali et al ., 2026). General illustrations are given figure 9 & 10.

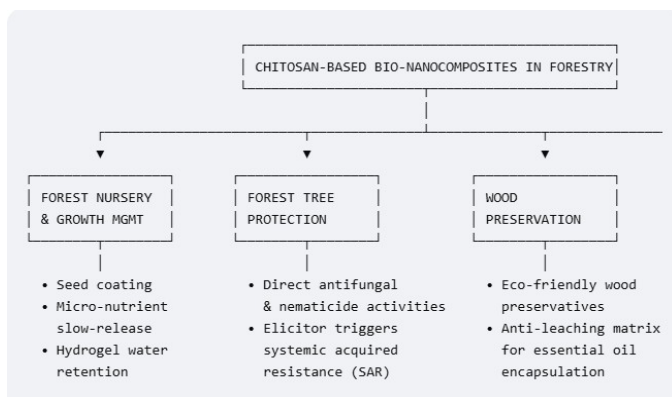


Figure 9. Role of Chitosan-based bio-nanocomposites in Forestry

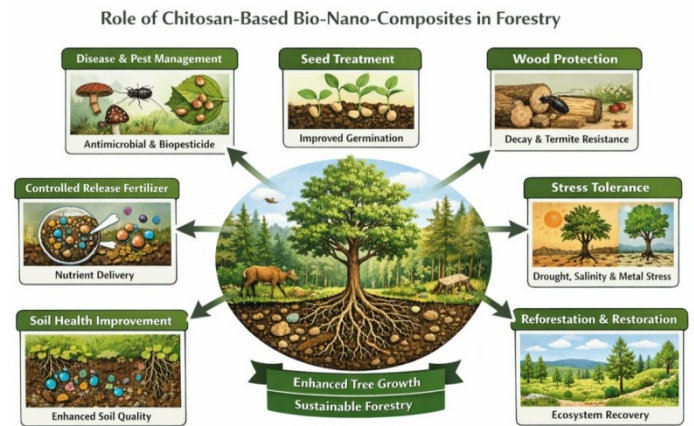


Figure 10. Role of Chitosan-based bio-nanocomposites in Forestry

When engineered at the nanoscale with inorganic nanofillers (such as metallic oxides or natural clays) or loaded into nanocarriers, these hybrid matrices exhibit drastically enhanced mechanical strength, barrier properties, and surface areas, making them powerful tools for modern forest management (Azmana et al , 2021; Kumar et al , 2025; Sali et al ., 2026) which has been briefed in following para:

1. Forest Nursery and Growth Management
2. **Smart Delivery Systems:** Chitosan nanoparticles serve as high-efficiency nanocarriers for the controlled, slow-release of fertilizers, plant growth promoters, and essential nutrients. This minimizes structural leaching caused by heavy rainfall and improves nutrient uptake by activating soil microorganisms.
3. **Seed Coating & Water Retention:** Applying nanocomposite films as coatings for forest tree seeds improves germination rates. Modified chitosan hydrogels can dramatically increase the water-

retention capacity of forest soils, mitigating drought stress in arid environments and newly planted clearings.

2. Forest Tree Protection (Biotic Stress Management)
 - **Direct Antimicrobial Activity:** The cationic structure of chitosan interacts directly with negatively charged fungal and bacterial pathogen membranes, causing cell disruption. For instance, nanocomposites have been effectively utilized to counter severe forest pathogens like *Phytophthora palmivora* in rubber tree populations.
 - **Defense Elicitation:** Beyond direct toxicity, nano-chitosan acts as a potent molecular elicitor. It mimics a pathogen attack, signaling the forest tree to trigger its Systemic Acquired Resistance (SAR). This prompts the upregulation of defense-related secondary metabolites (phenols, flavonoids) and antioxidative enzymes (catalase, peroxidase), which has been proven to significantly suppress devastating pests like the pinewood nematode. (Azmana et al , 2021; Kumar et al , 2025; Sali et al ., 2026)
 - **Wood Preservation and Timber Industry Optimization**
 - **Eco-Friendly Wood Coatings:** Traditional wood preservatives rely heavily on toxic heavy metals (e.g., copper, chromium, arsenic). Chitosan-based bionanocomposites serve as clean alternatives, providing durable physical barriers against wood-decaying fungi and termites.
 - **Essential Oil Encapsulation:** Advanced formulations utilize nano-chitosan matrices to encapsulate volatile plant essential oils. This architecture drastically reduces

chemical leaching in outdoor structural timbers while maintaining long-term wood durability and structural longevity. (Azmana *et al* , 2021; Kumar *et al* , 2025; Sali *et al* ., 2026)

Environmental Remediation and Heavy Metal Stress

- **Soil Restoration:** Chitosan composites feature abundant amine (NH_2) and hydroxyl (OH) groups that possess strong heavy metal chelating capabilities. Applied to degraded forest lands or mine-tailing reforestation zones, they immobilize toxic industrial metals (e.g., Lead, Cadmium, Chromium). This prevents metal absorption into tree roots, mitigating plant cellular dysfunction and preventing the contamination of the broader forest food chain. (Azmana *et al* , 2021; Kumar *et al* , 2025; Sali *et al* ., 2026).
- **Role of Chitosan-Based Bio-Nanocomposites in Moisture Stress Mitigation:** Chitosan-based bionanocomposites have emerged as an innovative, sustainable technology to alleviate the destructive impacts of moisture (drought) stress on agricultural crops and forest plantations. Characterised by a nanoscale size matrix (10–200 nm), these materials offer enhanced bioavailability, massive surface area, and superior absorption compared to bulk chitosan. (Rojas-Pirela *et al* , 2024; Choudhary *et al* ., 2026; Rishesh, *et al* ., 2026; Ullah *et al* , 2026) . Major role and mode of function in stress management is illustrated in Fig. 11 & 12.

When engineered with structural nanofillers or conjugated with functional molecules, these hybrid materials trigger physical, biochemical, and physiological adaptations that help plants preserve water and maintain cellular integrity during severe water deficits. (Choudhary *et al* ., 2026).

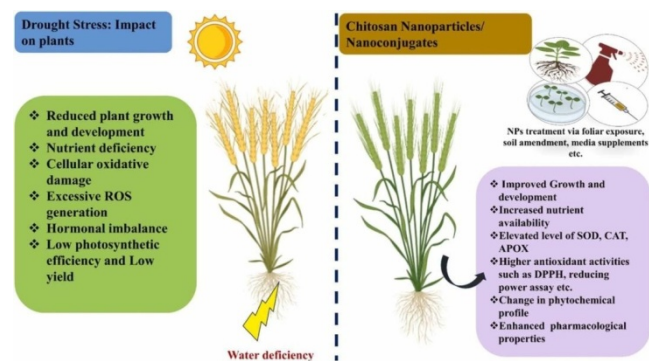


Fig. 11. Major role in stress management

A study conducted by Dubey (2026) was conducted to study the effect of Bio-Nano Composites in different combinations was studied on Avenue forestry species and it was demonstrated that nano-fertilizer interventions (Bio-Nano Composites) significantly enhance the growth dynamics and physiological resilience of diverse forestry species. The treatment of Bio-Nano Composites emerges as the effective strategy for accelerating biomass accumulation and mitigating environmental stress. This formulation provides a vital dual benefit: it accelerates essential biomass accumulation in ideal conditions and preserves plant vigor under environmental drought stress, serving as an actionable tool for sustainable forestry in arid and moisture-stressed ecosystems (Dubey, 2026).

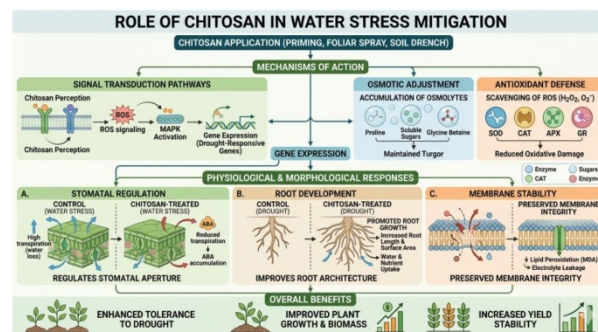


Fig. 12. Major mode of action in stress management

Physiological Regulation and Transpiration Control

Stomatal Modulation: Foliar application of nano-chitosan induces targeted stomatal closure by signaling the accumulation of endogenous abscisic acid (ABA) and hydrogen peroxide in guard cells. This drastically minimizes water loss through transpiration without halting cellular respiration.

Photosynthetic Preservation: During periods of low water field capacity, the nanocomposites protect and stabilize photosynthetic pigments (chlorophyll *a* and *b*). This preserves electron transport efficiency and safeguards the plant's structural biomass growth under severe stress. (Rojas-Pirela *et al* , 2024; Choudhary *et al* ., 2026; Rishesh, *et al* ., 2026; Ullah *et al* , 2026)

Biochemical Adaptation and Osmotic Adjustment

Osmolyte Accumulation: Chitosan bionanocomposites upregulate key metabolic pathways, driving the accumulation of compatible intracellular osmolytes such as proline, soluble sugars, and polyols. This helps maintain cellular turgor pressure and structural membrane stability.

Reactive Oxygen Species (ROS) Scavenging and GABA Shunt Activation: Water deficit triggers destructive reactive oxygen species (ROS). Nano-chitosan activates a powerful enzymatic defense framework—including Superoxide Dismutase (SOD), Catalase (CAT), and Peroxidase (POD)—while stimulating (gamma)-aminobutyric acid (GABA) synthesis to buffer cellular acidosis and prevent oxidative cell death. (Rojas-Pirela *et al* , 2024; Choudhary *et al* ., 2026; Rishesh, *et al* ., 2026; Ullah *et al* , 2026).

Rhizosphere Matrix Engineering

Hydrogel Water Retention: Integrated into the soil, chitosan cross-linked nanocomposite hydrogels act as micro-reservoirs. They swell to hold multiple times their weight in water, modifying soil porosity and preserving localized moisture around active root networks.

Root System Architecture: This localized moisture, combined with the biostimulatory nature of chitosan, alters root morphology by extending secondary root branching. This maximizes the plant's volumetric water-mining capacity from deeper soil strata. (Rojas-Pirela *et al* , 2024; Choudhary *et al* ., 2026; Rishesh, *et al* ., 2026; Ullah *et al* , 2026)

Controlled-Release Nano-Conjugates

Smart Nutrient Sourcing: Drought significantly impedes natural nutrient transport. Chitosan bionanocomposites resolve

this by encapsulating vital minerals (like Zinc, Potassium, or NPK complexes) or signalling molecules (like Nitric Oxide). This design facilitates a slow, controlled release of vital inputs, protecting resources from climate-driven leaching while sustaining plant vitality. (Rojas-Pirela *et al* , 2024; Choudhary *et al* ., 2026; Rishesh, *et al* ., 2026; Ullah *et al* , 2026).

CONCLUSION

Nanotechnology in forestry and plant sciences is a rapidly evolving field that manipulates matter at the atomic or molecular scale (1 to 100nm) to improve plant health, forest productivity, and wood product sustainability. In view of above study, it is relevant to mention that application of nanotechnology into forestry proposes a justifiable approach for enhancing biomass production and protecting ecosystems, particularly through specific nutrient delivery, stress resistance and enhanced pathogen defense mechanisms. Application of these innovative solutions to large-scale in forestry is critical for nurturing resilient forests and enabling a viable bio-economy (Rawat *et al* ., 2025; Dubey, 2026).

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