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Scopes and relevance of biopolymer-based nanostructures in sustainable agriculture

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ABSTRACT

Sustainable agriculture plays a crucial role in meeting the growing global demand for food while minimizing adverse environmental impacts from the overuse of synthetic pesticides and conventional fertilizers. In this context, renewable biopolymers being non-toxic, biodegradable, and eco-friendly offer a viable solution to improve agricultural sustainability and production. Judicious application of these biopolymers in the form of nano-sized functional molecules reduces the need for conventional pesticides and fertilizers, thus promoting safer farming practices and minimizing environmental contamination. These biomaterials have complex hierarchical structures, great stability, adjustable mechanical strength, stimuli-responsiveness, and self-healing attributes. Controlled bioactive ingredient released from biopolymers allows the tailored administration of agrochemicals, bioactive agents, and biostimulators as they enhance nutrient absorption, moisture retention, and root growth. Potential biopolymeric nanostructures maintain crop health by appending antimicrobials and biosensing entities while their eco-friendliness supports sustainable agriculture. Implementing these biopolymers is therefore anticipated to lead sustainable farming practices that prioritize resource efficiency, reduce chemical inputs, and enhance climate resilience.

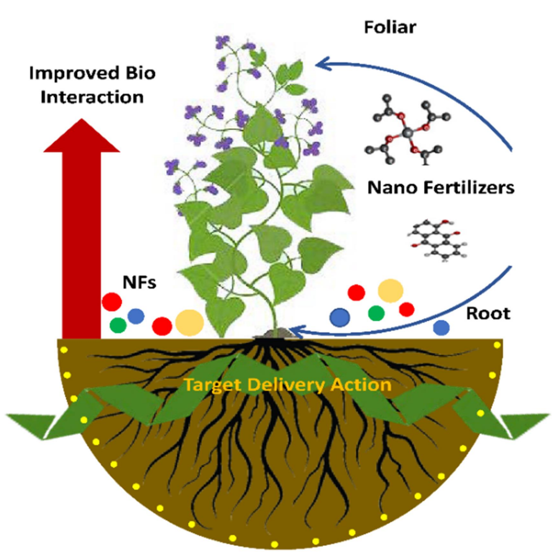
Keywords: Biopolymer, biostimulators, nanostructures, controlled-release fertilizers, nanofertilizer

1. Introduction

Sustainability in agricultural practices deals with environment friendly utilization of soil nutrients, water resources, minimal use of fertilizers, plant damage control, and superior farming techniques. Continuing warming of the atmosphere, reduction in rainfall in areas of rainfed crop production, increase in pests due to warming, and other climate-change-related impacts, pose real and serious threats to global, national, and local food security and sovereignty. In this pursuit, the indispensable use of fertilizers has emerged as an essential practice for augmenting crop yields and preserving soil fertility. Conventional fertilizers, such as urea, diammonium phosphate and muriate of potash are widely utilized to supplement crucial nutrients in the soil. However, conventional fertilizers suffer from low nutrient utilization efficiency due to leaching, leading to substantial economic losses and decreased soil fertility. The leaching of these nutrients from the soil has resulted in a significant decrease in soil fertility. This is primarily due to the relatively low nutrient utilization efficiency of conventional fertilizers, which is around 30–35% for nitrogen, 18–20% for phosphorus, and 35–40% for potassium (Yadav *et al.,* 2023). Moreover, the environmental impact caused by releasing excess nutrients has necessitated the development of more efficient and eco-friendly fertilizers. Hence, it is integral to increase slow/control launch fertilizers now not solely to amplify crop manufacturing and quality, however additionally to beautify the sustainability in agricultural production. With this concern, the concept of nanotechnology has been introduced in the field of agricultural betterment in order to ameliorate agricultural productivity through improving the utilization effectivity of important agrochemicals (pesticides, herbicides, fertilizers etc). With the use of nanotechnology, agriculture may benefit from more effective disease detection and control, precision farming with nano-sensors, increased production with nano-fertilizers and pesticides, and better food safety and quality with novel packaging materials. Nanotechnology deals with the handling of extremely small particles that have at least one dimension in the range of 1 to 100 nanometres, demonstrating the ability to become an integrated system of different active principles consisting of particles and perform functioning inside any experimental organism to ultimately make the desired organism more beneficial in terms of functioning in every aspect.

2. Potential nanomaterials for sustainable agriculture

Materials that are of up to 100 nm particle size in at least one dimension are generally classified as nanomaterials (NMs) and are the basis for nanotechnology. The conventional metallic NMs include single or multiwalled nanotubes, magnetized iron nanoparticles, copper (Cu), aluminium (Al), silver (Ag), gold (Au), zinc (Zn) and zinc oxide (ZnO), silica (Si), cerium oxide (Ce_2O_3), and titanium dioxide (TiO_2) derived nanostructures. With the unique properties of NMs such as high surface-to-volume ratio, controlled-release kinetics to targeted sites and outstanding adsorption capacity, nanotechnology has an excessive relevance for synthesis and application of nano-enabled new generation fertilizers (Altammar, 2023). Nowadays, nanofertilizers are seen as a potential substitute for conventional fertilizers, and in many cases, they are even preferred above them.



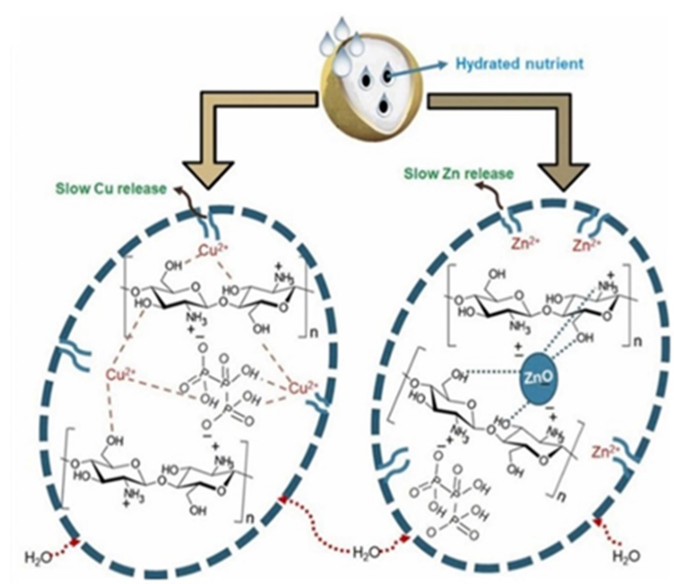


Figure 1 Controlled/slow-release nanosized fertilizers foster the plant growth and immune system by providing nutrients/active ingredients for a prolonged time period

They can be grouped according to their consistency, activity, and nutritional makeup. For example, inorganic and/or organic nutrient-loaded, controlled-release, plant growth-stimulating, water- and nutrient-loss-controlling, and nanocarrier-based nanofertilizers. The granular forms of controlled-release fertilizers (CRFs) make them potential nanomodule that efficiently deliver nutrients to plants over a prolonged period of time, from weeks to months (Yadav *et al.,* 2023). Furthermore, controlled-release fertilizers can increase agricultural sustainability by minimizing nutrient release into the environment (Figure 1). Their compact size, high surface area-to-volume ratio, and capacity to be coated with a variety of materials to modulate the release rate improve nutrient delivery efficiency. These ingredients can help increase the granular mechanical strength of fertilizers and enhance leaching resistance.

Research revealed plant roots, which act as nutrient portals, have a far higher nanoparticle permeability than that of typical manuring materials. The absorption of nanomaterials and their penetration deep inside leaves have also been seen to be facilitated by leaf stomatal apertures (Figure 2).

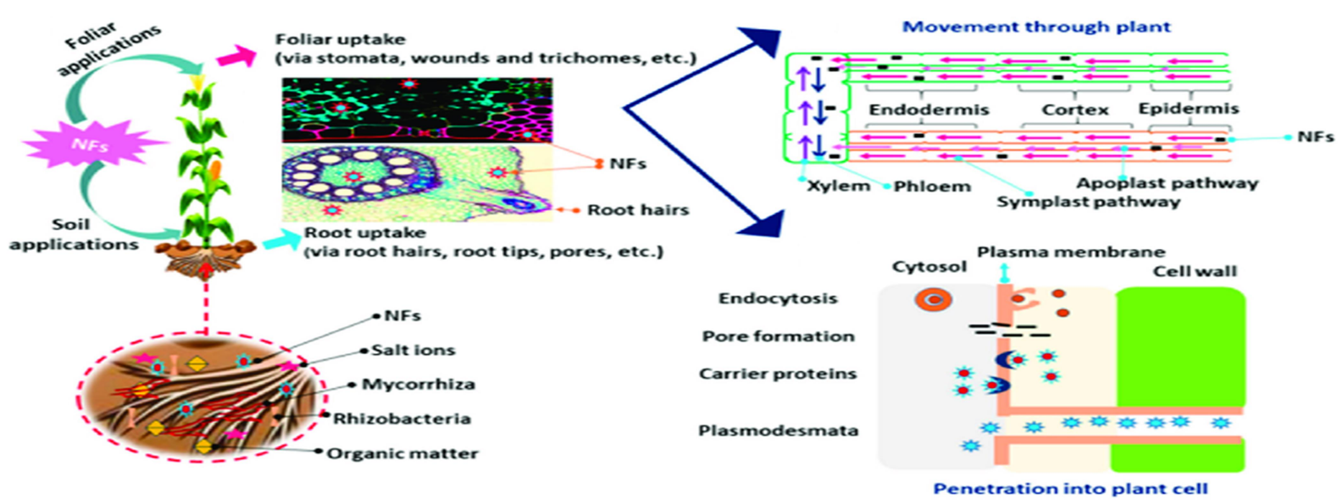
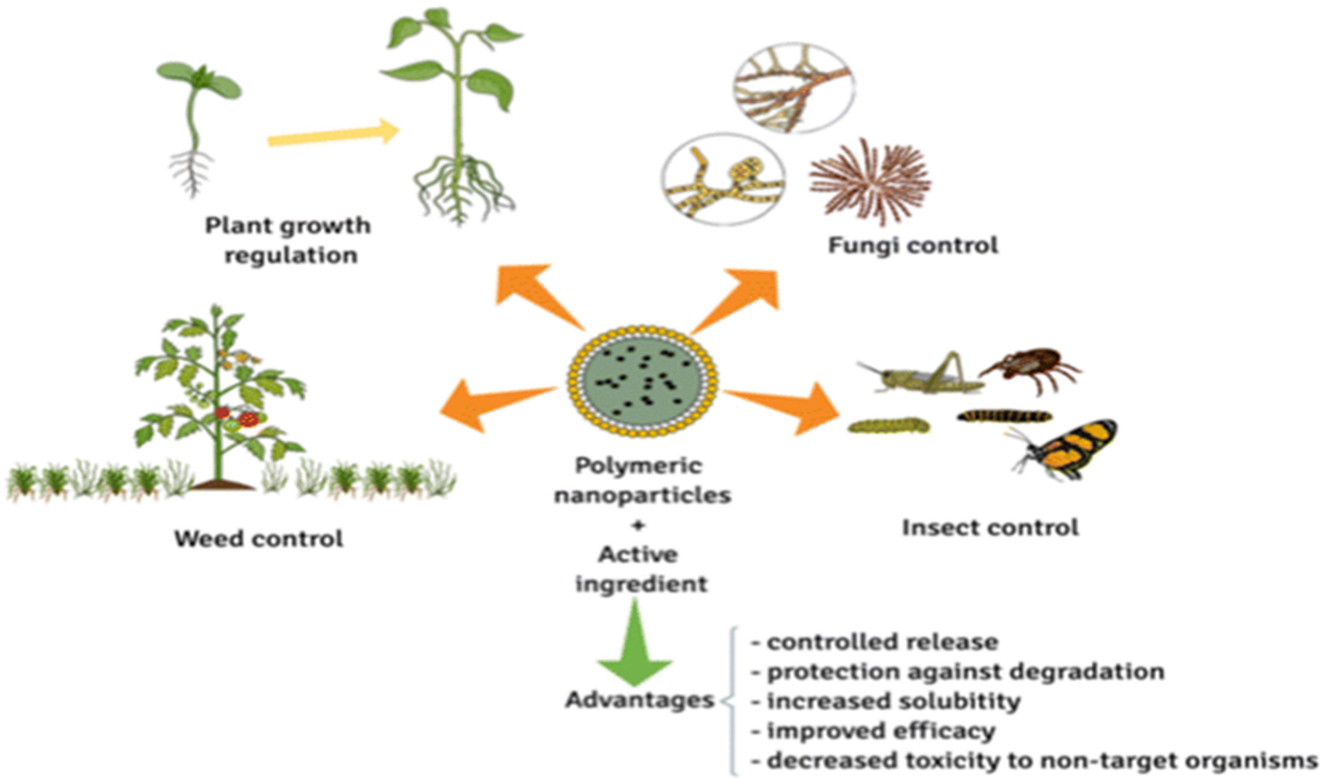


Figure 2 Application of Nano fertilizers either by foliar spray or basal and their uptake in the plant system

Despite their manageable benefits, issues about transport, toxicity, bioavailability, and environmental influences restriction their adoption in sustainable agriculture and horticulture sectors. Risk evaluation and hazard identification are crucial, and toxicological lookup priorities ought to be established. The phytotoxicity of NMs relies upon species, dose, utility method, and kind of NMs. Understanding the diploma of toxicity of every NM in a crop is crucial for appreciation their uptake, translocation, transformation, and accumulation.

3. Biopolymer based nanomaterials: biodegradable and biocompatible alternatives

Despite the potential use of metallic NMs in agriculture, research on nanofertilizer toxicity in crop plants is still in its early stages. Many studies have demonstrated that using metallic NMs in plants might cause an oxidative surge owing to interference in the electron transport chain (Ali *et al.,* 2020). Furthermore, the interference impairs detoxification of reactive oxygen species, which may have genotoxic consequences in the plant. When biosynthesized NMs are employed, there are little worries about toxicity. This is mostly due to the decreased usage of harmful chemicals during NM production, which makes the process more environmentally friendly and sustainable (Das *et al.,* 2017). Traditional techniques for synthesizing NM are energy-intensive and can include the use of toxic solvents, which can lead to the production of dangerous byproducts. Therefore, it is anticipated that greater attention will be paid to environmentally benign methods of developing biopolymeric NMs from various biological sources.



Biodegradable natural polymers derived from renewable resources have currently been appreciated in the field of nanotechnology for sustainable agriculture (Figure 3). Enhancing the physicochemical and mechanical characteristics of these polymers frequently necessitates chemical treatment. According to Darwish *et al.* (2022), nanocomposites that are composed of polymers combined with nanoparticles have better mechanical behaviour, increased adsorption, thermal stability, mem-brane permeability, and greater fouling resistance. Biopolymers have agricultural uses since they are biodegradable, biocompatible, bioactive, and hydrophilic. Natural biopolymers derived from plants, animals, and microorganisms are good alternatives to manufactured pesticides. Furthermore, biopolymers are benign in nature, and a polymeric formulation of bioactive compounds is quite straightforward to generate. Polymeric nanoparticles encapsulate bioactive chemicals and prevent them from deterioration due to external influences such as weather. Biopolymers (e.g., chitosan, alginate, guar gum, cashew gum) can also be utilized as slow-releasing nanocarriers to transport agrochemicals to plants (fertilizers/nutrients) as well as to treat infections (fungicides, bactericides, virucides) and pests (pesticides) (Sikder *et al.,* 2021).

Currently available biopolymers having tremendous potential to be utilised as nano-carrier of useful nutrients have been mentioned below (Table 1).

Table 1 Mostly available biopolymers having excellent agricultural potential

Bio-polymers	Source	Properties / activities
Chitosan	Shells of crustacean	Biocompatible, biodegradable, non-toxic, film-forming ability, highly bio-adhesive
Starch	Cereals, grains and potatoes	Tasteless, odourless powder insoluble in alcohol or cold water
Cellulose	Cell walls of oomycetes, several types of algae, and green plants	Biocompatible, biodegradable, non-toxic, highly tensile with compressive strength
Tamarind seed polysaccharide	seed of the Indian date, tamarind (*Tamarind indica* L.)	High viscosity, adhesivity, non-carcinogenicity, broad pH tolerance, biocompatibility
Guar gum	Guar seeds (*Cyamopsis tetragonoloba*)	Thickening and stabilizing agent, viscous pseudoplastic, low-shear viscosity, less sensitive to pH
Alginate	Brown algae	Biocompatible, biodegradable, anti-microbial agent, improve nutrient uptake and utilization mechanism in plant system
Carrageenan	Shells of red seaweeds	Non-toxic, gelling agent, bio-adhesive
Cashew gum	Exudate of the cashew tree (*Anacardium occidentale* L.)	Biocompatible, gelling agent, viscosity enhancer, surfactant in controlled delivery system, coating agent

(**Source:** Kumar *et al.,* 2022)

4. Future directions and conclusion

Nanotechnology is playing a major role in agriculture in different aspects like agronomy, soil health management, crop nutritional security, and crop protection from both the biotic and abiotic stress factors. The use of nanoparticles is increasing in daily base products but the mechanistic insight of nanoparticles, their penetration inside the desired system is still lacking. On the other side, nanoparticles beyond a certain limit show toxic effects on living system and environment. These nanoparticles reach at top of food chain by the process of biomagnification, when plants are treated with nanoparticles for enhancing the crop yield. Nano-structured biopolymers provide specialized solutions to a variety of agricultural difficulties, including improving plant growth and development, boosting soil fertility and structure, improving water retention, and fostering crop resilience in arid regions. One of the primary benefits of these biopolymers is their capacity to release nutrients and agrochemicals in a regulated way, which reduces environmental contamination and optimizes plant nutrient uptake. They also serve as intelligent delivery systems, allowing for precise administration of bioactive compounds to specific areas, hence increasing effectiveness and limiting undesired consequences. Biopolymeric functional nanostructures can also be employed to activate defense molecules and cell walls, initiating specific signalling pathways against diseases and pests. However, further research is necessary to completely grasp the potential of biopolymers in agriculture, as these structures provide effective and sustainable farming practices that guarantee food security, safeguard the environment, and look up the economics of modern agriculture.

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