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Nano-fertilizers: A Smart Delivery System Towards Increased Crop Production

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Abstract

With the increasing population of the world, meeting the food needs for all has become a major challenge. Depending solely on the conventional farming systems is not coming to fulfil the global requirement. The application of high doses of inorganic fertilizers is another issue towards the gradual soil health loss. In this aspect incorporation of nano-technology in fertilizer technology has come up with promising solution. Being extremely small in size and higher surface area, the absorption and translocation of these nano-fertilizers particles increases the effectiveness of fertilizer application and nutrient use efficiency. They can be applied either through foliar sprays, soil treatment or as seed nano-priming. They enter the plant cells and through cytoplasmic transport, interfere with various metabolic functions. But, these nano-particles can also be hazardous if they are applied at extremely higher doses as those can be entered through the food chain and through adsorption. Hence, safety concerns are required to regulate the dose of application towards a safer limit.

Introduction

Agriculture plays a crucial role in supporting the world's expanding population and propelling its booming economy. As a result of this endeavor, fertilizer application has become a crucial procedure for maintaining soil fertility and increasing crop yields. Conventional fertilizers are commonly used to augment vital nutrients in the soil. These include urea, nitrogen, phosphorous, potassium, monoammonium phosphate, and diammonium phosphate. However, leaching causes conventional fertilizers to have a low nutrient use efficiency, which results in substantial economic losses and decreased soil fertility. Soil fertility has significantly decreased as a result of these nutrients evaporating from the soil. The main cause of this is the very low nutrient utilization efficiency of traditional fertilizers, which is approximately 18–20% for phosphorus and 30–35% for nitrogen. Satisfying the present and future global food needs is one of the major challenges that the modern agricultural systems are facing. It is essential to substantially increase the nutrient use efficiencies together with implementing environmentally sound agronomic practices and exploring new innovations in the crop production technologies. The exploration and implementation of slow-release fertilizers have been already shown fruitful results to some extent. The horizon of increasing the nutrient use efficiency can further be expanded with adoption of nanotechnology in agricultural sectors. In fact, nanotechnology has made it possible to develop "smart fertilizer", new facilities that improve nutrient usage efficiency and lower environmental protection costs by using nanoscale or nanostructured materials as carriers of fertilizer or as vectors for controlled release (Wang *et al.*, 2021). Nano-fertilizers have emerged as a promising solution to address such challenges, offering higher efficiency and reduced environmental impacts.

Advantages of nanomaterials over corresponding bulk materials

At the nano level, matter exhibits remarkable properties that bulk materials do not display. One of the main differences between a nanoparticle and a bulk material is the presence of a large fraction of the atoms on the surface of the nanoparticle. Compared to macro-sized particles, nanoparticles can have different surface composition, different types of sites and different reactivities in terms of processes like adsorption or redox reactions that could potentially be used in the synthesis of nano-materials for agricultural applications. Nano-fertilizers have higher surface area which makes them easier to for the absorption by crops and have better solubility and retention capacity in soil thus making more available for the crop's uptake. Table 1 gives an idea of the advantageous prospects of using nano-sized fertilizer materials over conventional fertilizers that are attributed to the properties of nano-fertilizers.

Table 1. Some of advantages related to transformed formulation of conventional fertilizers using Nanotechnology

Desirable Properties	Examples of Nano-Fertilizers Enabled Technologies
Controlled release formulation	The nano-structured formulation might permit fertilizer intelligently control the release sped of nutrients to match the uptake pattern of crop.
Solubility and dispersion for mineral micronutrients	Nanosized formulations of mineral micronutrients may improve the solubility and dispersion of insoluble nutrients in soil, reduce the absorption, fixation and increase the bio-availability to the crops.
Nutrient uptake efficiency	Nanostructured formulations might increase fertilizer use efficiency and uptake ratio of the soil nutrients in crop production and save fertilizer resource.
Controlled release modes	Both release rate and release patterns of nutrients for water-soluble fertilizers might be precisely controlled through encapsulation in envelop forms of semi-permeable membranes coated by resin polymers, wax and Sulphur.
Effective duration of nutrient release	Nano-structured formulation can extend increase effective duration of nutrient supply of fertilizers into the soil.
Loss rate of fertilizer nutrients	Nano-structured formulations can reduce the loss rate of fertilizer nutrients into the soil by leaching or leaking.

Mode of entry to plants

The plant cell wall serves as a barrier to allow easy entry of all external agents including nano particles into the plant cell. The sieving property of the plant cell wall is determined by the pore diameter (5 to 20 nm) of the cell wall. Therefore, only nano particles with a pore diameter less than the cell wall pore diameter can easily pass through and enter the plasma membrane. In addition, there is a chance of enlargement or induction of the cell wall pores due to interaction with engineered nano particles, which in turn enhance the uptake of nano particles. Nano particles are further internalized through endocytosis (a cavity-like structure formed around the nanoparticles by the plasma membrane). Nano particles may also pass through the membrane using embedded transport carrier proteins or ion channels. When applied to the leaf surfaces, they enter through the stomatal openings or through the base of trichomes and thereby are translocated to different tissues. However, the accumulation of nano particles on the photosynthetic surface results in foliar heating and changes in plant physiological and cellular functions (Stomatal obstructions) (Figure 1).

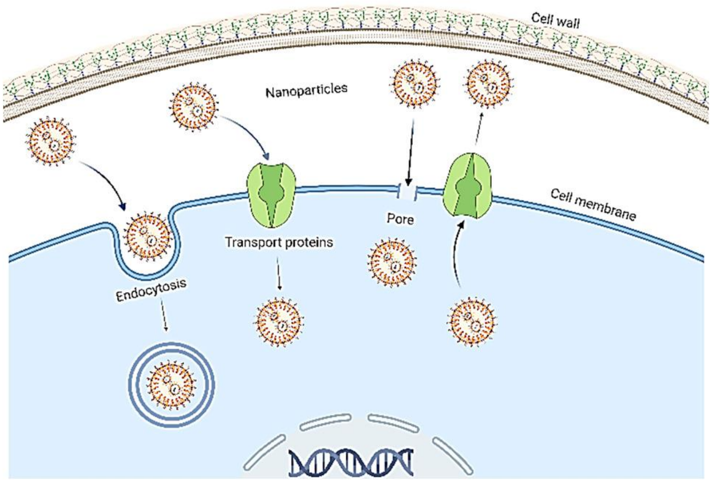

Figure 1: Nanoparticle entry in plant cells

Uptake, translocation and fates of nano-fertilizers in plants

The uptake, translocation, and fate of nano-fertilizers depend on the age, plant species, environmental conditions, and the physiochemical property, functionalization, stability and the mode of entry of the nano-particles. The entry of nanoparticles through the cell wall is dependent on the pore diameter of the cell wall (5–20 nm) (Fleischer *et al.*, 1999). Hence nano-particles with diameter less than the pore size can easily enter the plant cells. After entering, the nano-particles can transport either apoplastically or symplastically. They might move from one cell to another by plasmodesmata (Rico *et al.*, 2011). When nanoparticles enter the cytoplasm, they approach to various organelles and interferes with the cell's many metabolic functions (Moore 2006).

Modes of application of nano-fertilizer formulations

There are three primary modes of application of nano-fertilizers to plants that includes- foliar sprays, soil application and seed nano-priming (Yadav *et al.*, 2023).

Foliar sprays

The application of nano-fertilizers through foliar spray has emerged as a promising method for delivering essential nutrients such as N, P, Zn etc. to plants. This approach is based upon the delayed release mechanism to enhance the effectiveness. Folar-applied nano-particles (NPs) can be absorbed by stomata, endocytosis, or direct absorption; however, the mechanism is highly dependent on particle size. The absorption of these particles may be impeded by barriers such as cell walls and leaf wax. The majority of NPs gather in vacuoles after absorption. Notwithstanding, a multitude of factors, such as plant traits, NP physical qualities, and ambient conditions, impact the absorption and transport of nanoparticles.

Seed nano-priming

This method entails soaking the seeds in nano-fertilizers and this has shown a significant reduction by half of the fertilizer application toward the achievement of maximum results (do *et al.*, 2021). Deployment of nano-priming technology has been found to increase seed germination by eliminating reactive oxygen species (ROS) and regulating plant development hormones (Sharma *et al.*, 2023). The conventional methods for seed priming involve the use of water, nutrients, or hormones to break down the seed coat. Advanced seed nano-priming methods, on the other hand, apply nano-fertilizers directly to the seed surface, leaving a significant portion that prevents disease penetration.

Soil treatment

Nano-fertilizers can also be applied as soil treatment. Once in the soil, the NPs interact with plant roots through adsorption to the root surface or by penetrating root cells via endocytosis (Ahmed *et al.*, 2021). When applied to soil, nano-fertilizers can interact with plants, soil particles, and microorganisms, which may alter their behavior and function. Although this method of application is considered reliable, there may be chances of uncertain long-term effects of NPs, higher cost and regulator challenges (Mishra *et al.*, 2019).

Safety issues towards the use of nano-fertilizers

Although nanotechnology has incredible potential to transform many aspects of human life, its benefits may come at a price. One of the biggest questions facing the world before the adoption of nanotechnology is whether the unknown environmental and health risks of nanoparticles outweigh their potential benefits. Although nanoparticles have not yet been linked to direct human disease, early experimental studies indicate that nanoparticles can initiate adverse biological reactions that can lead to toxicological consequences (Nel *et al*. 2006). Nanoparticles which constitute a part of ultrafine particulate matter can enter in the human/animal system through oral, respiratory, or intradermal routes. Nano-fertilizers enable nanoparticles to enter in the food chain allowing their distribution in every organism related to the food chain. Therefore, it is essential to regulate amount of nano-particles application to a sufficiently safer limit.

Conclusion

The excessive use of chemical fertilizers, although can increase the crop yield, the large use of these is not suitable for the long run. Also, the nutrients contained in the bulk commercial fertilizers are not fully accessible to crops. In view of this, the adoption of nano-fertilizers can be a promising option towards the higher nutrient use efficiency and sustainable crop development. Nano-fertilizers can precisely release their active ingredients in responding to environmental triggers and biological demands. However, the uptake, translocation and fate of the particles in the plant system are largely unknown, leading to various ethical and safety problems related to the use of nano-fertilizers in crop production. Thus, we must ensure that the nano scale particles are not being used indiscriminately and are applied at the required level.

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