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Nano fertilizers: A Sustainable Technology for Improving Crop Nutrition and Food Security

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Abstract

The significant reliance on chemical fertilizers in current agricultural techniques, precise crop nutrient control, and soil fertility will pose significant challenges in the coming decades. The injudicious use of synthetic chemical fertilizer has created environmental and human health challenges over the world. Nano fertilizers have a variety of effects on nutrient uptake, plant growth, and development by providing nutrients in the root zones. The efficiency of plant growth, soil quality, and crop production of cereals and other crops are all significantly improved by nano fertilizers. Additionally, it strengthens defenses and increases resistance to stress. There are several methods for loading nano fertilizers, such as direct manufacturing of nutrient-based nanoparticles, encapsulation in the nanoparticulate, and absorption on nanoparticles. Plant species, growth stage, climate, and the size and stability of nanoparticles are affected the absorption and translocation of nano fertilizers in plant tissues. A rapidly emerging cutting-edge agricultural technology for agricultural advancement is nanoparticles. The primary focus of this review, which is based on very recent research, is on the role and interaction of nano-enabled fertilizers with crops and how nano fertilizers can help more effective and sustainable agriculture in the future.

Keywords: Nano-particles, Nano-fertilizer, Plant nutrient

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Introduction

Abiotic and biotic stresses brought on by climate change in ecosystems between the environment and food production lead to crop failure (Mittal et al., 2020). Due to population growth, our global food demand is predicted to increase by almost 70% by 2050 (Mandal D. 2021). The challenges of fulfilling the increasing food demand put tremendous pressure on agriculture for producing sufficient food that creates demand for agriculture inputs like fertilizer.

One of the best ways to boost crop productivity, sustain yield increase, and ensure food security is through fertilizer application. In order to improve crop output and provide nutrients, fertilizers are frequently applied through soil surface broadcasting or in conjunction with irrigation; nevertheless, this practice may have negative effects on ecosystems, water bodies, and the environment (Adisa et al., 2019). Inorganic fertilizers have been the cornerstone of all forms of contemporary agriculture since the Green Revolution. Around the world, synthetic fertilizers -inorganic fertilizers that have been created in the right dosage to give nutrients are used to increase agricultural yield and plant development. Researchers are drastically looking for a suitable technology for increasing the nutrient use efficiency as the fertilizer materials are applied to soil. A major portion of nitrogenous fertilizers are lost and others fertilizers also have some disadvantages regarding the efficiency. The scientific community introduces nanotechnology in agriculture to improve the current situation of fertilizer.

One quickly developing trans-disciplinary area of the current sciences is nanotechnology. It reached its peak in the 1960s and 1980s, and ever since, it has been expanding the path of innovation and advancing research. Nanotechnology, which works with materials ranging in size from 1 to 100 nm, is changing matter on a molecular and atomic level. It is believed that agriculture and food systems could be altered by nanoscale research and nanotechnologies. Because of molecule reduction and changed molecular interactions, materials' properties change at this scale.

The sole purpose of green nanomaterials (Khan et al., 2017), nano fertilizers (Fatima et al., 2021), nano agrochemicals (Gomez et al., 2021), nano pesticides (Grillo et al., 2021), nano herbicides (Kumar et al., 2020), nano biosensors, and nano-based agricultural waste treatment is to implement sustainable agricultural management and boost food productivity through foliar and soil application.

In order to increase crop yields while maintaining a healthy agro-ecosystem in the face of environmental challenges, nanotechnologies are increasingly being adopted in agriculture (Rajput et al., 2021; Lowry et al., 2019). In order to increase the use efficiency of current fertilizers, either by improving the delivery of poorly bioavailable elements or by limiting losses of mobile nutrients to the surrounding environment, future agriculture may be based on the use of nano-enabled fertilizers in a variety of ways (Yin et al., 2018). This review paper includes an overview of the potential use of nano-enabled fertilizers in a variety of crops, their effects on the nutritional value and stress tolerance of crops, their potential endpoint in the environment, and their potential effects on ecosystems.

Nanotechnology in agriculture

The term "nanoscale," an acronym for the International System of Units (SI), denotes a 10^{-9} reduction. Systems that are larger than molecules and smaller than macroscopic ones (usually >1 nm and 100 nm) are included in the nano-sized world, which is commonly measured in nanometers (1 nm equals 10^{-9} m). The nanotechnology includes nano-biosensors that measure soil moisture content and nutrient status and can also be used for site-specific water, nano fertilizers that can effectively manage nutrients, nano-herbicides that can selectively control weeds in crop fields, nano-nutrient particles that can increase seed vigor, nano-pesticides that can effectively manage pests, and nano carriers for herbicides such as chitosan nanoparticle (Khot LR, 2012). Nano-herbicides work well for controlling weeds (Pereira et al., 2014). The properties of nano fertilizers can differ from those of bulk materials since they are aggregated with at least one dimension smaller than 100 nm (Tarafdar et al., 2014). The value chain of the whole agricultural production system can be expanded through the manufacturing of nano fertilizers.

Nano fertilizer

The application of nanotechnology to food production and agriculture has drawn more attention. Different chemical, physical, mechanical, and biological processes can produce nano fertilizers, or they can be extracted from different plant parts that are vegetative or reproductive. It is employed to improve soil fertility, plant productivity, and the quality of agricultural products (De Rosa et al., 2010). For example, by decreasing phosphorus fixation in the soil, the conversion of rock phosphate to nano form may increase the amount of phosphorus available to the plant (Adhikari et al., 2010). Nano fertilizers, which can be liquid or solid and have a size of less than 100 nm, have been used to give plants nutrients or to increase the efficiency of conventional fertilizers. Plants can swiftly and completely absorb nano fertilizers.

Nano fertilizers are essential in modern agriculture because of their efficient formulations and delivery methods (Mittal, 2020; Adisa et al., 2019). In order to improve nutrient usage efficiency and environmental quality, researchers are looking into using nano fertilizers based on various metals and metal oxides in agriculture. These nanoscale fertilizers minimize nutrient losses from leaching and prevent chemical modifications (Raliya et al., 2017; Saharan et al., 2016).

Because of their smaller size and potential for unique absorption dynamics, nanoscale particles provide significant advantages over bulk particles or ionic salts. (Subbaiah et al., 2016; Dimkpa et al., 2017). The use of nano fertilizers may improve the efficiency of nutrient delivery to plants since they have been demonstrated to promote productivity by guaranteeing targeted delivery/gradual release of nutrients and minimizing fertilizer application with an increase in nutrient use efficiency (Kah et al., 2018; Chhipa, 2017). Nano fertilizers are produced from standard fertilizer bulk materials or extracted from different plant components using a variety of chemical, physical, mechanical, or biological techniques in order to improve cereals, fruit, increase crop output, and implement soil fertility (El-Ramady HR, 2014).

There are two methods for creating nanomaterials: top-down and bottom-up. The top-down approach; this method reduces the size of a bulk material to create nanoparticles. Examples include mechanical milling, laser ablation, and lithography.

Bottom-up approach: This approach involves assembling atoms or molecules into larger nanostructures. Examples include sol-gel methods, chemical precipitation, and self-assembly.

These are nanomaterials designed to improve plant nutrient uptake and growth. They can be produced using various methods:

Physical: Processes like gas condensation, where nanomaterials are formed from vaporized materials, are used.

Chemical: Chemical reactions, such as sol-gel synthesis or chemical vapor deposition, can create nano fertilizers.

Mechanical: Techniques like ball milling can be employed to reduce bulk materials into nanoparticles for fertilizers.

Biological: Nanomaterials can be synthesized using biological processes, such as using plant extracts to reduce metal ions into nanoparticles.

Furthermore, physical, chemical, mechanical, and biological processes are the main ways that nano fertilizers are produced. A study by Zhang et al. (2014) states that nutrients can also be encased in nano fertilizers or covered with a thin layer of nanoparticles. Nano fertilizers can also be stabilized or encapsulated using synthetic polymers. The chemical properties of the nutrients and transporters used to make nanoparticles can be ascertained in a number of methods, including:

i) Emulsion-Solvent Evaporation method (Jaiswal *et al.,* 2004).

ii) Double Emulsion and Evaporation method (Ubrich*et al.,* 2004).

iii) Salting Out method (Catarina PR, 2006).

iv) Emulsions- Diffusion method (Vargas *et al.,* 2004).

v) Solvent Displacement / Precipitation method (Chorney *et al.,* 2002).

Characteristics of nano fertilizers and form

Nanomaterials are categorized in a variety of ways, according on their dimensions (Hett A. 2004)

a) Nanoparticles have only one dimension.

b) Nanoparticles with two dimensions.

c) Nanoparticles with a third dimension.

While TEM is used to assess the size and morphological characteristics of liquid (suspension or solution) nanoparticles, SEM is utilized to measure the properties of amorphous or crystalline nano fertilizers. The manufactured nano fertilizers' particle size distribution, zeta potential measurements, and particle size distribution are all measured using the Malvern Zetasizer analyzer (Nano ZS). There are several ways to load nutrients onto nanoparticles, including; (a) Nanoparticle absorption, (b) Ligand-mediated attachment to nanoparticles, (c) Encapsulation in a polymeric nanoparticle shell, (d) Polymeric nanoparticle entrapment and (e) The creation of nutrient-based nanoparticles.

Macronutrient nano fertilizers

According to Chhipa (2017), macronutrient nano fertilizers are chemically made up of one or more nutrients (such as N, P, K, S, Ca, and Mg) that are needed in significant quantities for plant growth and development. Among the macronutrients C, H, and O, crops may readily absorb them from the atmosphere. The research claims that application to the soil results in a significant loss of resources, with the main macronutrients (N, P, and K) being lost 40%–70%, 80%–90%, and 50%–90% (Zulfiqar et al., 2019).

Nano-biofertilizer

Even though fertilizers based on nanoparticles are very important in agriculture, their direct application into the soil has been shown to have several drawbacks, including low stability, poor shelf-life, and negative effects on the environment and performance factors (pH, temperature, and radiation). Because of the negative effects of conventional fertilizers, including their long-lasting effects and harm to the environment, nano-bio fertilizers have recently gained popularity over chemical fertilizers.

Uptake of nanoparticles in plant leaves

Pathways for Foliar Uptake

Usually, the leaf surface is sprayed with the nanoparticles, which then deposit there. The particles are then taken up by the plants through their cuticle or stomata. The waxy cuticle on the leaf epidermis is mostly composed of wax, cutin, and pectin. It protects plant leaves from water loss during growth and serves as the primary natural barrier to keep nanoparticles out of the leaves (Yang et al., 2015). Two separate channels, one hydrophilic and the other lipophilic are present on the surface of the waxy stratum corneum, according to Avellan et al. (2019). The diameters of the hydrophilic and lipophilic channels range from 0.6 nm to 4.8 nm, per Eickert et al. (2008). The hydrophilic channels allow for the diffusion of hydrophilic nanoparticles having a diameter of less than 4.8 nm (Banerjee et al., 2019). The lipophilic channels in the surface of the cuticle allow lipophilic nanoparticles to be absorbed by leaves through infiltration and diffusion.

Hu et al. (2020) recently showed that carbon dots smaller than 2 nm may enter cotton leaves through the cuticular channel using confocal fluorescence microscopy, which has great spatial and temporal resolution. However, due to the microscopic pore channels in the cuticle, plants can only absorb a specific quantity of nanoparticles through the epidermis. It has been observed in many studies that nanoparticles can move to other plant tissues during this time. Another technique the researchers proposed for absorption of nanoparticles is the stomatal channel (Figure 1).

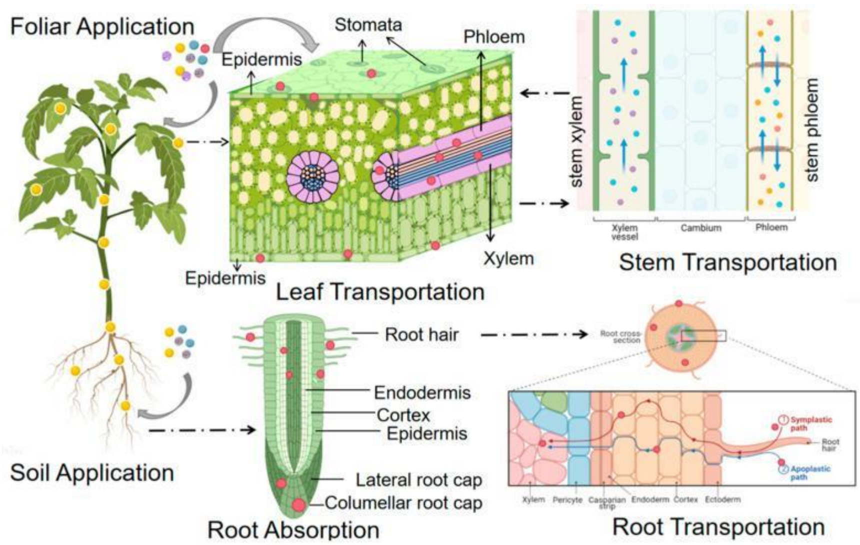

Fig. 1. A schematic diagram of the uptake and translocation of NPs in plants through foliar application or root exposure treatment (Wang et al., 2023)

The stomata on the leaf surfaces of plants are responsible for controlling the flow of water and gasses. Typically, stomata are between 10 and 100 µm in size. The size and density of stomata vary among different plant species. The exact size exclusion limit (SEL) of the stomatal aperture for the diffusion of nanoparticles is yet unknown due to the unique geometric layout and physiological function of stomata (Ha et al., 2021).

Factors affecting uptake nanoparticles via Leaves

According to recent studies, the environment, plant species, and the type of nanoparticles all affect how well they are absorbed by plants. The way that nanoparticles absorb in plant leaves can be influenced by their size, chemical makeup, surface charge, and surface modification. The size of the nanoparticles has become one of the most crucial variables in the investigation of NP absorption in the blade because of the size exclusion limit of NPs in the absorption pathway (Li et al., 2020).

Effect of Size and Chemical Composition

The size and chemical composition of the nanoparticles has variation on the uptake mechanism. The absorption mechanism is affected differently by the size and chemical makeup of the nanoparticles. It has been discovered that the stomatal channel allows metal-based nanoparticles smaller than 50 nm in diameter to enter plant leaves (Ha et al., 2021). The capacity of leaves to absorb nanoparticles declined with an increase in particle size. Numerous investigations have demonstrated the foliar absorption of nanoparticles. The application ZnO nanoparticles (30 nm) tagged with fluorescein isothiocyanate (FITC) to wheat leaves. Through the use of confocal microscopy, they discovered that zinc oxide nanoparticles primarily entered wheat leaves through the stomata channel, where they subsequently aggregated in chloroplasts (Zhu et al., 2020). It has been demonstrated that stomatal width reductions are correlated with a drop in zinc concentration of 33.2% and 8.3%, respectively, in the chloroplast and cytoplasm of wheat leaf cells. Avelian et al. (2019) applied coating-modified gold nanoparticles with varying diameters (3, 10, 50 nm) to wheat leaves. It was discovered that wheat (*Triticum aestivum* cv. cumberland) leaves could absorb coated gold nanoparticles of various sizes (Avellan et al., 2019).

Effect of Shape and Surface Charge

The shape and charge of nanoparticles play an additional role in their ability to enter plant mesophyll tissue, in addition to their size. Differently shaped nanoparticles have distinct interfacial characteristics that alter their surface area and contact angle with the plant surface, eventually influencing the absorption of nanoparticles (Bandala and Berli, 2019). Plant leaves have the ability to absorb nanoparticles that are negatively or positively charged. The impact of surface charge on the adsorption of ZnO nanoparticles on wheat leaves and the absorption of surface charge on graphene quantum dots (GQDs) on maize leaves has been examined in earlier research. The findings demonstrated that maize leaves may absorb positively-charged NH2-GQDs (13 nm) and negatively-charged OH-GQDs (14 nm) through their stomata. Confocal microscopy confirmed that FITC-labeled F-P-ZnO NPs (40 nm) with a positive charge and F-N-ZnO NPs (40 nm) with a negative charge gathered at the stomata on the surface of wheat leaves. The electrostatic attraction between positively-charged nanoparticles and negatively-charged plant cell walls is primarily responsible for the stronger adsorption of positively-charged nanoparticles in the leaves compared to negatively-charged nanoparticles (Bandala and Berli, 2019).

Effect of Plant Species

One of the key elements influencing how well nanoparticles are absorbed by plant leaves is plant species. The size, density, and location of the pores in leaves are all factors in the absorption of nanoparticles. For instance, the stomata of monocotyledonous plants are placed neatly and have regular forms, in contrast to dicotyledonous plants. The plant's life cycle and stage of growth have an impact on how well nanoparticles are absorbed by the leaves. Some plant species have stomata on both the top and lower epidermis, while the majority of plant species only have stomata on the lower epidermis (Dimkpa et al., 2017). In dicotyledon plants with bilobe leaves, the number of stomata on the lower epidermis was approximately 1.4 times more than that on the upper epidermis. There was almost the same number of stomata on both sides of monocotyledon plants. Furthermore, abiotic environmental elements like light, humidity, and temperature have an impact on stomata's opening and shutting, which in turn has an impact on NP absorption.

Absorption of nanoparticles in plant roots

Pathways for Root Uptake

Adsorption on the root surface is how nanoparticles and plant roots first come into touch. Positively charged nanoparticles are more likely to concentrate in the root and be readily absorbed on the root surface due to the root hairs' ability to exude chemicals like mucus or organic acids, which results in the root surface having negative charges (Chhipa, 2017). It is possible for nanoparticles to infiltrate the root column through the creation of new adsorption interfaces by lateral root development. The root cell wall's epidermal cells are semi-permeable. Large particles may be prevented from passing through the tiny holes in the root cell wall (Rajput et al., 2021). According to other research, certain nanoparticles have the ability to rupture the plasma membrane and cause the skin's cell wall to develop new pores, which opens up a pathway for large-diameter nanoparticles to enter. Plant cells can absorb nanoparticles by a variety of mechanisms, including the ion route, endocytosis, interaction with cell membrane proteins, and physical damage.

Important factors influence nanoparticle uptake through roots

The size, chemical makeup, and surface charge of nanoparticles are among the many variables that greatly influence their absorption by plant roots.

Effect of Size and Chemical Composition

The most significant element influencing the root absorption of nanoparticles is thought to be their size. Previous research has demonstrated that particles smaller than 10 nm, like CeO_2 nanoparticles (8 ± 1 nm) (Rawat et al., 2017), can be absorbed by plant roots. This has been observed in the roots of maize and Vicia faba L., respectively. Wheat roots, for instance, are capable of absorbing TiO_2 nanoparticles with a particle size range of 36-140 nm. The TiO_2 NPs larger than 140 nm are not able to be absorbed. Due to the size restriction, it is commonly accepted that metal-based nanoparticles have a difficult time being absorbed by plants through their roots if their particle size is greater than 100 nm (Renner et al., 2020).

Effect of Surface Charge

The surface charge of NP influences its uptake by plants in addition to its size. The surface charge characteristics of nanoparticles that plant roots can absorb are determined by the negative charge of the cell walls of plant roots. Plant roots and leaves experience slightly varied effects from electric charge on the absorption of nanoparticles (Khalkhal et al., 2020). Because of the electrostatic attraction between the positively charged nanoparticle and the negatively charged cell wall, positively charged nanoparticles tend to cluster on the root surface but are unable to penetrate the root tissue (Li et al., 2017). The roots of Arabidopsis thaliana may absorb the uncharged and negatively charged nanoparticles (22 nm) and subsequently allow them to enter the xylem of the plant. By contrast, the positively charged nanoparticles of Arabidopsis can only collect at the root epidermis; they are unable to penetrate the root tissue (Barber, 1995).

Nanoparticles mechanism of action

The main mechanisms underlying nanomaterial toxicity that we observed in this section include (1) ATP production, DNA replication, and gene expression; (2) generation of reactive oxygen species (ROS); (3) damage to cell membrane integrity; (4) interruption of energy transduction; (5) release of toxic components; and (6) protein destabilization and oxidation. Figure 2 depicted the method of action of the nano fertilizer.

Influence on gene expression, DNA replication, and ATP synthesis

At very low concentrations, nano ions can interact with respiratory chain enzymes like NADH dehydrogenase, leading to the uncoupling of respiration from ATP generation. In addition, the binding of ionic nanoparticles to the transport protein results in the proton motive force collapsing and proton leaking. In contrast to the advantageous applications of DNA-nanomaterial conjugation, fullerenes have been discovered to bind DNA and induce strand deformation, which has a negative influence on the function and stability of the molecule. The oxygen radicals found in titanium dioxide nanoparticles, which are employed in sunscreen, have the ability to nick supercoiled DNA. Despite these findings, nothing is known about the potential mutagenic effects of nanoparticles due to the paucity of research on the genotoxicity of nanoparticles using Ames tests or other procedures (Karimi and Mohseni Fard 2017).

The di-nitrogen availability and NO_3 accumulation for later fixation may be affected if nitrification genes are stimulated without concurrently stimulating denitrification genes (which convert NO_3 to N_2). Genes linked to stress as well as those pertaining to

S, Cu, and Fe balance are activated, indicating additional molecular disruptions. Moreover, other metal control genes are impacted by silver nanoparticles, suggesting that they have an impact on cellular metal homeostasis (Minghetti and Schirmer 2019).

Reactive oxygen species (ROS) generation

One of the main ways that nanoparticles cause toxicity is by lowering oxygen molecules, and different kinds of nanoparticles generate different kinds of ROS. The majority of ROS are produced by the mitochondria as byproducts of oxidative cellular metabolism. The four known types of ROS are hydrogen peroxide (H_2O_2), singlet oxygen ($^1O_2$), superoxide anion radical (O_2-), and hydroxyl radical (OH-) (Yin et al., 2012, Fu et al., 2014). ROS are produced when nanoparticles are absorbed and are in charge of cellular oxidative stress, the development of nanotoxicity, which includes DNA damage, apoptosis, cytotoxicity, cell signaling manipulation, and the promotion and initiation of cancer (Zhu et al., 2013). DNA is the biological target of ROS. Oxidative DNA damage includes base and sugar lesions, DNA-protein crosslinks, single-strand and double-strand breaks, and the development of basic sites. Numerous studies have demonstrated that ROS influence distinct signal transduction pathways in a range of cell types and systems, which in turn controls cell physiology and function and plays a significant role in some biological processes (Vara and Pula 2014). Numerous investigations have also demonstrated the critical role ROS play in the interaction between microbial cells and DNA. Additionally, ROS raised the expression of genes in oxidative proteins, a crucial process in the death of microbial cells. According to Wang et al. (2017), ROS can also damage proteins and lower the enzymatic activity of specific periplasmic enzymes that are necessary for microbial cells to preserve their typical morphology and physiology.

Mechanisms by which plants absorb and accumulate nano fertilizer from the soil

The dispersion, aggregation, stability, immobilization, bioavailability, and transport of NPs are influenced by the physicochemical properties of the soil, including its texture, structure, clay minerals, pH, cation exchange capacity, soil organic matter, and microbial population (Khalkhal et al., 2020). According to Li et al. (2017), the surface charge effect of dissolved organic matter influences the aggregation, mobility, stability, and binding behavior of nanoparticles.

It is possible to spray nano fertilizers directly onto plant leaves or the ground. In order of appearance, the root entrance comes after the foliar entry. While foliar application, which is accomplished by spraying the green canopy or leaves, largely acquires access through the cuticle, stomata, and hydathodes, root treatment gains access through the root tips, lateral roots, root hairs, and rhizodermis. Foliar application of nano fertilizers is preferred under poor soil and weather conditions (Mittal et al., 2020). The movement of water and solutes through soil is described by the Richards equation, the convection-dispersion equation, which has been applied to a number of empirical models, and the Michaelis-Menten equation (Barber S.A. 1995).

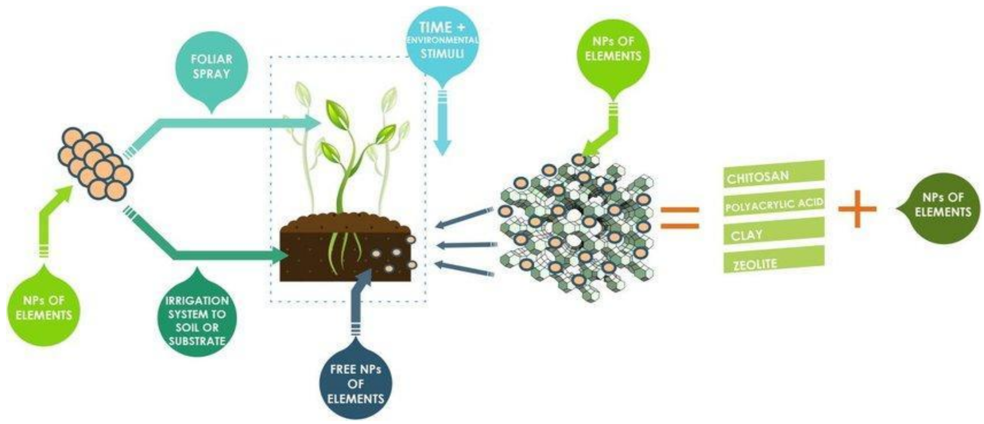

Diagram: Crop application of nano fertilizers. The recorded nanomaterials with critical ingredients that are released under controlled conditions in response to environmental stimuli or time are shown on the right. The vital elements' nanoparticles on the left are applied straight to the soil, irrigation water, or the surface of seeds, fruits, or plants. (A Moraiaz, et al., 2017)

Absorption climbs in a nonlinear fashion as nutrient concentration rises, reaching maximum uptake. The kinetic parameters of the Michaelis-Menten equation depend on a number of factors, including the type of plant, growth duration, soil temperature, and others. The first nutrient transport model for plant tissues was the steady-state source-sink model with flow driven by an osmotically created pressure gradient influenced by diffusive transport factors (Payvandi et al., 2014). Nevertheless, further research is needed to create an ideal uptake model or mechanism for nanoparticles in plants.

The effect of nano fertilizer on photosynthetic leaf gas exchange capacity

The physiological and biochemical indices of agricultural plants improved dramatically with the use of nano fertilizers. A biocompatible magnetic nanofluid (MNF) increased the beneficial effect on sunflower leaves' total chlorophyll content. Applying titanium oxide (TiO_2) topically was found to increase crop yield by improving photosynthetic pigments in corn. According to Sebesta et al. (2021), adding TiO_2 to spinach increased the photosynthetic rate by about 29% and enhanced nitrogen metabolism, protein concentrations, and green pigments by up to 17 times.

The relationship between plant growth, biomass, and productivity and nano fertilizers

Because the morphological characteristics of nanocarriers may influence how nutrients are delivered via membrane surfaces, it is imperative to demonstrate the utility and worth of nano fertilizers. The morphological and physiological traits of both germinating seed and foliar treatment to boost seedling growth, biomass, germination ability, and seed vigor index were found to be positively impacted by nCHT in chickpea, maize, and tomato seedlings (Saharan et al., 2015).

For crops with a high yield value, seed priming prior to sowing appears to be a viable technique. NPs may interact with biological elements like chloroplasts once they have entered the cytoplasm. Since mesoporous silica nanoparticles (MSNs) do not harm plants and enhance photosynthesis by acquiring enough light-harvesting chlorophyll-protein complexes, they might be safe in this type of intelligent distribution (Bhat et al., 2021). For plant nutrition, silica is essential since a deficiency weakens plants and makes them more vulnerable to outside stresses.

Nano fertilizers mitigate Abiotic Stresses

ENMs' massive surface area and nanoscale size have greatly improved biological systems' functionality by promoting plant growth and development in the face of biotic and abiotic stressors such as temperature, salinity, alkalinity, drought, and metal and mineral toxicity (Kah et al., 2018; Pullagurala et al., 2018; Sharifi et al., 2020). Titanium dioxide (TiO_2), which is known to alter photoreduction activity in the electron transport chain (ETC) present in chloroplasts and is in charge of oxygen evolution, blocks linolenic acid.

Importance and limitation

Nano fertilizer, the most significant area of agriculture, has drawn more attention because of its potential to increase yield, enhance soil fertility, reduce pollution, and foster an environment that is favorable to microorganisms (EPA 2004). It also provides more surface area for various metabolic reactions in the plant, which increases the rate of photosynthesis and produces more dry matter and crop yield (Tarafdar and Raliya, 2013). The advantages are (a) nano fertilizers increase nutrients efficiency, (b) reduce environmental damage and soil toxicity, (c) minimizes the frequency of the application, (d) decreased depletion of fertilizers, (e) adjust the speed of nutrient released and (f) improving the crop efficiency and increase crop yield by providing the nutrients through slow release to the plant.

Recent advancements in the use of nano fertilizer to increase crop yields are evidence of its effectiveness. Before being used commercially, the possible risks to plants, soil organisms, and human health should be thoroughly evaluated, even if the use of nano fertilizers is undoubtedly opening up new avenues for intelligent and sustainable agriculture. Human health may be at danger from the buildup of nanoparticles in the environment and food chain.

Conclusions

Numerous nanoparticles have demonstrated genuine promise in crop yield and agriculture. However, a lot more seems to be needed to advance scientific understanding and bring about another green revolution for global food security in the age of climate change in the years to come. Recent developments in nano fertilizers could be explored to achieve economically and environmentally sustainable precision agriculture. Using nano fertilizers instead of inorganic fertilizers has many benefits, such as improved soil fertility, less pollution, enhanced agricultural productivity, and the creation of an environment that is favorable for microorganisms. In order to feed the world's population while maintaining a healthy ecology, future research into a second green revolution has found that nano fertilizers are essential.

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