

# APPLICATION OF NANOTECHNOLOGY FOR FORTIFICATION OF PLANT NUTRITION AND ENHANCEMENT OF PLANT PRODUCTION

## Abstract

Human health has been negatively impacted by nutrient deficiencies in food crops, particularly in rural areas. Nanotechnology may provide the most long-term solution to this problem. The nutrients in food can be enhanced in a number of approaches, including dietary variation, medication use, and industrial fortification. The cost-effectiveness and long-term viability of these approaches haven't been fully accomplished, yet. Fertilizers provide nutrients for plants, nevertheless, the majority of conventional fertilizers are ineffective at nutrient delivery nutrient use, and uptake efficiency. Therefore, nanofertilizers have been developed to be target oriented and difficult to lose. This overview covers the impacts of adding macro and nanonutrients into the soil, nutrient content in food, crop interactions, ecological impact, and absorption ability of crops.

**Keywords:** nanotechnology, biofortification, nanofertilizers, sustainable agriculture

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## I. INTRODUCTION

The most recent precision agricultural technology uses nanotechnology to create and direct strategies toward satisfying the increasing human population's demand for food. The urge to apply nanotechnology in agriculture comes from the fact that the world's population continues to rise and there is an increasing demand for food. According to population estimates, around 9.6 billion people by 2050 [1]. Nanotechnology, in which strategies are drawn up and directed to respond to growing food demand from the increasingly urban population, is an important technology for precision agriculture.

New weather patterns brought by climate change last for at least a few decades and, in some cases, for millions of years. These climate changes are resulting in new challenges for agricultural crops, food security, dietary intake, food safety, and human health. They are also changing biodiversity, crop adaptation, new cropping patterns, and incidences of pests and diseases. Evidence reveals that the essential circumstances for good health, clean air, water, food, shelter, and the prevention of pests and diseases are already being impacted by the current climatic changes. Moreover, human activities and societal changes are causing farmlands to lose fertility. These are always detrimental to crop production, which is likely to lead to famine and malnutrition, so efforts must be made to improve plants in order to increase yields.

Utilizing cutting-edge technologies for improving plant nutrient uptake, disease diagnosis, and treatment etc., nanotechnology has the potential to revolutionize many areas of agriculture and the food industry. Precision agriculture using nanotechnology offers enormous potential to increase the yield and quality of food crops through biofortification. Nanotechnology exploits the nanoscale material having 1-100 nm size and a high surface area to volume ratio. Nanoparticles exhibit special targeted properties such as higher strength, strong electrical conductivity, and additional chemical reactivity. In addition, the nanoparticles have  $10^{-9}$  diameters along with unique chemical, physical, and biological characteristics. Nanoparticles or nanomaterials can be produced by using different methods, like top-down and bottom-up approaches. Breaking down bulk materials into nanosized structures is an essential step in the top-down approach to producing nanomaterials. Poor control over nanoparticle size and a higher level of impurities are two drawbacks of this approach. Contrarily, the bottom-up approach of synthesizing nanoparticles includes building up the material atom by atom, molecule by molecule, or cluster by cluster. This approach has superior control over particle size and also eliminates impurities because it is a chemically controlled production method. Additionally, nanoparticles can be produced organically, a process known as biomanufacturing. For this, a variety of biological systems, including bacterial, fungal, and plant systems, can be used. Greater control over the particle's toxicity and size is an advantage of this approach.

Chemical fertilizer use has existed for a long time and significantly enhanced agricultural yields. However, they cause an imbalance of soil minerals, ruin the soil structure, soil fertility, and overall ecology, all of which are severe long-term hindrances. It is important to create intelligent materials that can release nutrients in particular sites and support a clean environment in order to deal with the situation. Recent research has demonstrated the potential of graphene as a nutrition carrier for crops. It promotes crop production with minimal environmental impact since it may give nutrients to the plants in a slow, regulated

manner. By utilizing the features of nanoscale materials, this technology utilizes better materials to enhance agriculture. The agricultural use of nanotechnology is bridging the nutrient loss and crop fortification gaps. Precision farming is a transition off from traditional crop production methods towards technologies that could be facilitated by the use of nanotechnology. Which has the potential to lower production costs, and maximize the resource use efficiency and productivity of crop plants that ensures nutrient security. It can enhance food quality and postharvest shelf life, boost rural or farmers' income, boost agricultural productivity with necessary nutrients, and support a pollution-free environment. In the nano-regime, farmers are using this science to increase their crops' quantity and quality.

Nanobiotechnology, livestock, nanotoxicology, agrochemicals, hydroponics, biotechnology, etc. are all examples of how nanotechnology is used in agriculture. Biofortification strategies include agronomic and breeding methods for enhancing the nutritional content of crops. In agronomic interventions, fertilizers are used such as organic, inorganic, and biofertilizers. But due to volatilization and leaching the inorganic fertilizers are usually or easily lost, while the use of organic matter is hampered by its low mineral content and a long period of nutrient release. So, it is important to apply nanotechnology in solving some of these issues. The goal of this study is to explore the most recent literature on the application of nanoparticles in the biofortification of plant nutrition and enhancement of plant production. In order to combat malnutrition, it is important to fortify crops with nutrients on a global scale. Biofortification techniques and the employment of nanoparticles in biofortification and enhancement of plant production are highlighted.

## II. FORTIFICATION OF NUTRIENTS

To fulfill the increasing population's hunger for food, finding ways to boost the nutritional value of crops and their key nutrients is crucial. Humans require around 40 nutrients and 20 minerals for healthy growth and development and derive their nutrition from food. But, most often human diets are poor in essential nutrients, thus leading to malnutrition[2]. The consequences of micronutrient deficiencies have a detrimental impact on health, intelligence, educational performance, and workability with untold consequences, which has a significant impact on long-term national development[3].

There are a number of ways to deal with micronutrient deficiencies, including dietary changes, industrial fortification, and biofortification. A fortified food diminishes the risk of heart disease, anemia, blindness, cancer, and early mortality; therefore, crops must be fortified. Dietary changes include fruits, vegetables, and animal and animal-based products. Nevertheless, nutrients found in plants are also necessary for the nutrition of animals and products made from animals. Thus, human deficiencies spin out of control if these plants are not fortified with micronutrients. Intake of micronutrients in the form of capsules, pills, or syrup is referred to as supplementation. Fortification and supplementation both require production and/or distribution facilities which may not ultimately be profitable for people living in remote areas. An example of supplementation is the 1990s-era vitamin A pill initiative. It may be challenging to provide fortified foods to people in rural areas who are unable to afford or consume them. As a result, the necessity for the biofortification of crops is considered a method of enriching crops or staples with nutrients while they are still in the field. Fortification of readily available food sources should be given the most importance,

with food supplements serving as a stopgap remedy. The goal of biofortification is to benefit people with low incomes and the general community.

### III. BIO-FORTIFICATION OF CROPS

Nutrient deficiencies are a major global health issue, which affecting millions of people worldwide. Poor access to diverse and nutritious food leads to malnutrition and its associated health problems. Growing varieties which are high in minerals and vitamins are known as biofortification. For example, to develop vitamin A rich sweet potato variety. Mass distribution of improved, nutrient-rich food is assured with biofortification. The goal of biofortification is to create sustainable, affordable staple crops with high nutritional value that may mitigate the negative impacts of micronutrient deficiencies. Despite the fact that daily amounts of important minerals and vitamins from biofortified staple crops are lower than those found in supplements or commercially enriched foods, they can nonetheless meet a person's daily needs for micronutrients[2]. Unlike industrial or commercial fortified foods, they give people in rural areas a way to find nutrient-rich foods locally. Agronomic biofortification, conventional breeding, and nutritional genetic alteration are some of the different biofortification methods.

Introducing Biofortification a groundbreaking solution that addresses nutrient deficiencies head-on. Through innovative breeding techniques, Biofortification enhances the nutritional value of staple crops by increasing their essential micronutrient content. With Biofortification, we can now provide communities with access to nutrient-rich foods that support optimal growth, development, and immune function. By incorporating these fortified crops into daily diets, we can improve overall well-being and combat malnutrition on a large scale.

**1. Biofortification by Crop Breeding & Genetic Modification:** Crop breeding is used for biofortification, which is the science that boosts the micronutrient content of staple crops while utilizing conventional breeding methods and modern biotechnology. Crops are developed and genetically altered to increase nutrient content and absorption ability. Plant breeding techniques tend to improve the level of micronutrients in different grains, legumes, and tubers. Breeding for biofortification has various benefits as a policy, including the production of daily staples and an emphasis on the needs of the underprivileged. Once again, these developed varieties may be used in the long run, which lowers costs and makes them sustainable. Agricultural biotechnology utilizes modern biological techniques to manipulate living beings or their components for cogent purposes in crops, allowing the infusion of genes from the wild, which cannot be done using conventional breeding. This has enabled the modification of crops in novel ways and is a tool for addressing global agricultural challenges. Farmers will be inspired to grow that new variety as a result. The nutritional deficiencies in human diets could be resolved by increasing the Fe, Zn, and Se content of crops by utilizing plant genetics and biotechnological methods; however, this method is costly and time-consuming [4]. It becomes difficult for crops to receive sufficient amounts of micronutrients in soil that is deficient in these crucial micronutrients, necessitating agronomic biofortification with fertilizers. The practice of plant breeding is the most widely employed sustainable fortification technique, developing new genotypes that are micronutrient-enriched takes a lot of time. The ability of new cultivars to increase micronutrient content is also

constrained by the amount of accessible micronutrients in the soil. Moreover, not many people might choose to eat these genetically modified, high-micronutrient crops. Agronomic biofortification is an alternate method to boost the micronutrient content in staple foods in order to get over the constraints of crop breeding biofortification methods.

- 2. Biofortification by Agronomic Method:** A rapid and simple approach to the deficiency of these essential nutrients in soils and plants is the agronomic method of biofortifying crops with micronutrients. It entails growing types that are nutrient- and vitamin-rich. With this technique, the micronutrient content of crops like grains and legumes is increased through fertilization. Crop rotational planting techniques, phytoavailable micronutrient fertilizers, routine soil alkalinity correction, and strategic introduction of symbiotic soil microorganisms are all used to increase the micronutrient content of crops. The fertilizers, cropping systems, and soil amendments as agricultural instruments for improving the nutritional content of crops. It has been noted that crops' micronutrient level falls even when their yield is high, most likely as a result of ongoing nutrient depletion without replacement by particularly high-yielding variety.[4] reported that by cultivating the six cereal crops on coal combustion residue rich in natural elements, the Fe, Zn, and Se content increased in crops. Agronomic fortification improvement depends on application techniques, type of fertilizer, packaging, and crop development stage at the time of application. Ordinary fertilizers are quickly absorbed by plants but easily drain out, which is a significant problem. Due to, leaching, microbial degradation, photolysis, and fixation of NPK and other agrochemicals have been observed to have a low use efficiency by plants[5].Even so, the difficulty of producing crops with high nutritional contents sustainably in spite of poor biophysical conditions along with other limiting factors.

#### IV. BIOFERTILIZERS

The nutrients in the soil are depleted periodically as a result of persistent cultivation and use of agricultural lands. As a result, it is essential to often nourish the soil. Low agricultural productivity due to depleted soil results in poor harvest, hunger, and malnutrition. Chemical fertilizers are simple and convenient for farmers to utilize for crop enhancement, but their high costs and inherent harmful effects demand quick attention.

Biofertilizers, sometimes known as "green fertilizers," are organic methods of enriching the soil by employing plants that decompose or animal manure, which bacteria consume to provide the essential nutrients for productive crop growth. Microbes play a crucial role in this natural fertilization process because, without them, plant or animal components would not be in a condition that growing crops could absorb and would not be beneficial to the soil. As an alternative, biofertilizers can be microbes that stimulate the natural nutrient uptake, high crop production, high quality, and stress tolerance processes in the soil and plants. These "plant growth-promoting rhizobacteria," which include blue-green algae, phosphorus-potassium solubilizing organisms, azotobacter, and Rhizopium, are primarily bacteria found in soil [6]. They interact with decomposing biological materials and fix atmospheric nitrogen to release nutrients for plant development. They behave symbiotically because plants are unable to thrive without them and because they themselves are dependent on plants to survive. They assist in defending the plants from pathogenic attack in addition to providing nutrients for the plants. Alternative biofertilization includes

the rotation of cereals and legumes in a crop-livestock combination. By using legumes to fix nitrogen and animal manure in combination with cereal legumes towards better soil texture and create an ideal habitat for the activity of microbes, this technique aims to increase soil nutrients. In general, organic farming produces crops of great value, but it can only be done in limited amounts, particularly by farmers in remote areas, and the output is expensive.

## V. INORGANIC FERTILIZERS

To supply the soil nutrients required for the cultivation of crops, inorganic fertilizers are required. Inorganic fertilizers are synthetic fertilizers derived from petroleum that can either be made up of one nutrient or a blend of several nutrient types. Multi-nutrient fertilizers are used when there are several different nutrients present. They can be complete or balanced and mostly comprise potassium, phosphorus, and nitrogen. When they have the same ratio, they're balanced, and if they are required by a specific formula, they are complete. The majority of the nutrients required for plant growth are provided by the soil, however occasionally during harvest the nutrients are depleted and must be supplied with fertilizers. Plants can develop and absorb the proper nutrients needed for crops with the aid of fertilizers. The macronutrients, mainly nitrogen, phosphorous, and potassium, make up the majority of traditional fertilizers, with just a small amount of calcium, sulfur, and magnesium. The lack of micronutrients including zinc, iron, copper, and manganese causes the crops to be deficient.

**1. Nitrogen Fertilizers:** Nitrogen is a macronutrient that enhances crop productivity. Which is commercially available in liquid and solid forms such as urea, urea-ammonium nitrates, and anhydrous ammonia; Urea is the most often used nitrogen fertilizer because of its high nitrogen concentration, affinity with various nutrients, ease of handling, and application. Upon being applied to the soil, nitrogen combines with water and releases ammonium ions, which are then converted to nitrate to create the nitrate ions that plants require. To ensure a plentiful crop, farmers occasionally apply overdose. However, these activities may harm the soil's health since they alter its structure and concentration. When the extra nitrogen compounds are leached into water bodies, it may also cause eutrophication.

When nitrogen fertilizers are applied, nitrification inhibitors, additives, or stabilizers, could be used to minimize the depletion of  $\text{NH}_3$  caused by the nitrification process of the fertilizers with the soil and water molecules. These substances, such as NBPT [N-(n-butyl) thiophosphorictriamide], boric acid, dicyandiamide (DCD), and 3, 4-dimethyl pyrazole phosphate (DMPP) can be mixed with urea or urea-ammonium nitrate fertilizers and assist in reducing the action of urease bacteria that converts the fertilizers to  $\text{NH}_3$ . Nitrogen when taken in the form of nitrates is difficult for clay soil or organic matter to absorb while ammonia frequently explodes into the air. The easiest way for the soil to absorb nitrogen fertilizers is in the form of ammonium ions.

**2. Phosphorus Fertilizers:** Phosphorus is the major nutrient in plants, which has a role in producing proteins and it is a crucial component of plants' nucleic acids. The plant uses it for sophisticated energy conversions, cell division, and the growth of new tissue. The energy produced during photosynthesis and the breakdown of carbohydrates are stored in phosphate molecules, which are later released to support plant growth and reproduction.

Phosphorus-deficient soils can cause plants to accumulate sugars and develop a reddish-purple tint from anthocyanin pigments. In the early stages of growing crops where phosphorus is most crucial; cereals can absorb up to 75% of their total phosphorus needs in the first 5–6 weeks following crop emergence[7].

The other sources of phosphorus fertilizers include bone meal and industrial wastes like basic slag and Thomas slag, in addition to the inorganic phosphorus fertilizers derived from the rock mineral apatite. The solubility of the phosphorous fertilizers is divided into three categories: citric soluble (dicalcium phosphate, Thomas slag, basic slag, defluorinated phosphate, and fused magnesium phosphate) and water-soluble (monobasic calcium phosphate and ammoniated superphosphates), and sparingly soluble phosphate (tricalcium phosphates).

3. **Potassium Fertilizers:** Potassium has a great role in Plant development and processes, without it plants cannot function properly. It is one of the three essential nutrients for ensuring crop quality, a stunning appearance, and great produce. It is important for a number of functions, including regulating water and stomata, growth, photosynthesis, protein synthesis, and many more. Lack of potassium in the soil prevents plants from absorbing potassium, making them more susceptible to illnesses, resistant to wind and temperature changes, and affecting the crop's general growth and development process. Spots under the leaves, curled leaf tips, interveinal chlorosis, and other signs may also be present [8].
4. **Secondary Fertilizers:** Calcium (Ca), sulfur (S), and magnesium (Mg) are secondary nutrients that are also required in substantial proportions, much like nitrogen, phosphorus, and potassium. When combined with the principal plant nutrients (NPK), secondary and micronutrients can be administered to crops in proportions that can remedy soil deficiencies and make them bioavailable. However, their excesses are bad for crop growth because too much calcium, whether in the form of calcium sulfate or calcium chloride, can raise pH due to the anions (Cl and SO<sub>4</sub>) and cause other nutritional issues.
5. **Micronutrients:** Important micronutrients include iron (Fe), boron (B), copper (Cu), zinc (Zn), manganese (Mn), molybdenum (Mo), nickel (Ni), chlorine (Cl), and molybdenum and which are required for crop development in minute amounts. Their lack can lead to structural issues, inadequate absorption of other nutrients, and decreased crop output. Although the main nutrients for crop productivity are nitrogen, phosphorus, and potassium, their excesses can cause an imbalance in the micronutrients. For instance, excessive use of nitrogen and potassium results in a shortage of magnesium, whereas excessive use of phosphorus leads to an imbalance in the amount of zinc present. Fe and Mn may be in appropriate forms but not all may be accessible to plants. On the other hand, due to its high mobility, boron can be hard to accumulate, particularly in sandy soils [8]. Some delicate crops, such as beans and grains, could become harmful as a result of starting fertilizers' excessive boron concentrations.

## VI. NANOFERTILIZERS

Agricultural systems could be revolutionized by nanotechnology, which provides a framework for the application of agrochemicals with an effective delivery system making it

secure, targeted, and easy to administer. Nanofertilizers are utilized in agriculture to improve plant nutrient uptake (Fig. 1). Any nanomaterial with the potential to improve plant nutrient uptake is referred to as a nanofertilizer. They could be combined with other macro or micronutrients to generate nanoforms of various fertilizers, such as nitrogen (N), phosphorus (P), and potassium (K). Three different kinds of nanofertilizers have been suggested: nanofertilizers (fertilizers in the form of nanoparticles), nanocoatings (conventional fertilizers put onto nanoparticles), and nanoadditives (the conventional fertilizers along with nanoscale additives).

Nanofertilizers tend to be more productive than the majority of the most recent polymeric-type conventional fertilizers because of their high surface area-to-volume ratio. Due to their nature, crops may be able to absorb nutrients effectively and slowly. As a result, this technology provides the framework for innovative and efficient nutrient delivery approaches that take advantage of the unique nanoporous surfaces of plant parts. With encapsulated nanoparticles, nanoclays, and zeolites, fertilizer application is more effective, soil fertility and plant health are restored, and environmental pollution and agroecological degradation are reduced.

The species of the plants or concentration, composition, and chemical properties of the nanomaterials, play a role in how well they work as fertilizers for plant growth. The creation of new technologies required to broaden the field of nano-agriculture for effective crop production depends on the extensive understanding of the fields of biology, biotechnology, material science, and engineering. Zinc oxide nanoparticles (ZnONPs), silica, iron, titanium dioxide, ZnS/ZnCdSe core-shell quantum dots (QDs), InP/ZnS core-shell QDs, Mn/ZnSe QDs, gold nanorods, Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>, CeO<sub>2</sub>, and FeO can each be found in nanofertilizers [9].

Chemical fertilizers are known to have adverse effects on the ecosystem, including emitting greenhouse gases, oxygen deprivation, leaching of nutrients and further polluting the groundwater aquifers, such issues require immediate action; thus, scientists are looking for alternatives like nanofertilizers. The nanofertilizer provides a slow release of nutrients (Fig. 1), which reduces the leaching of the nutrients.

Nanomaterials possess unique properties like low particle size, large surface-to-volume ratio, and excellent optical properties, offering opportunities for plant development, nutrient security, and diverse farm practices. The 21<sup>st</sup> century revolution in nanotechnology has led to improved fertilizers in the form of nanofertilizers, which can be easily absorbed by soil and improve plant growth. Conventional fertilizers lack all the necessary nutrients for plant growth, making it an interesting venture to engineer materials for nanofertilizers that address nutrient and environmental issues associated with conventional fertilizers [5].

Nanofertilizers offer advantages (Figure 1) over conventional fertilizers by enhancing nutrient effectiveness, reducing chemical fertilizer usage, making crops drought and disease resistant, and being less hazardous to the environment. Their high surface area to volume ratio makes them easily absorbed by plants. The size and morphology of nanoparticles determine bio-accessibility. Fortification with nanonutrients can bridge nutrient deficiencies and be engineered to address specific deficiencies in plants.[10]investigated the impact of silicon dioxide nanoparticles on the cucumber (*Cucumis sativa*), and the findings showed that



applying SiO<sub>2</sub> nano fertilizer increased the content and uptake of nitrogen and phosphorus while decreasing the content and absorption of sodium. According to these findings, silicon dioxide nano fertilizer may help cucumber plants' yield and development.

The porous materials' or the soil's strong adsorption of metals and anionic nanoparticles, which renders ions excessively available as dietary nutrients or even pollutants when undesirable. "Nano-Leucite Fertilizer" a patented nanofertilizer, which is eco-friendly, can reduce nutrient loss in food, with an overall increase in crop production. In short, nanofertilizers have the ability to increase fertility levels in nutrient-deficient soil, making them the most effective thing that might happen in the agricultural revolution. It could be viewed as "one more tool in the toolkit," though. The list of approved nanofertilizers included in (Table 1)[9].

**Table 1: List of world approved nanofertilizers and their compositions**

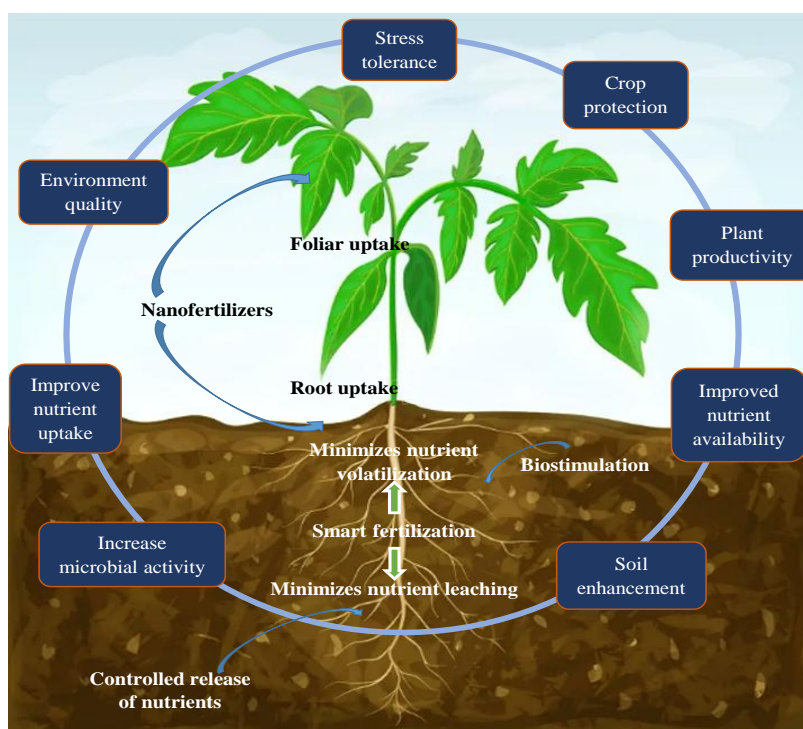
Sr. No.	Nanofertilizers	Manufacturer	Constituents
1	IFFCO Nano Urea	IFFCO Nano Biotechnology Research Centre (NBRC)	N, 4%
2	Biozar Nano-Fertilizer	Fanavar Nano-PazhooheshMarkazi Company, Iran	Combination of organic materials, micronutrients, and macromolecules
3	PPC Nano	WAI International Development Co., Ltd., Malaysia	M protein, 19.6%; K <sub>2</sub> O, 2.1%; Na <sub>2</sub> O, 0.3%; diluent, 76%; (NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> , 1.7%;
	Nano Capsule	The Best International Network Co., Ltd., Thailand	N, 0.5%; P <sub>2</sub> O <sub>5</sub> , 0.7%; K <sub>2</sub> O, 3.9%; Ca, 2.0%; Mg, 0.2%; S, 0.8%; Fe, 2.0%; Mn, 0.004%; Cu, 0.007%; Zn, 0.004%
4	IFFCO Nano DAP	IFFCO Nano Biotechnology Research Centre (NBRC)	N, 8%; P <sub>2</sub> O <sub>5</sub> , 16%
5	Nano Calcium (Magic Green)	AC International Network Co., Ltd., Germany	CaCO <sub>3</sub> , 77.9%; MgCO <sub>3</sub> , 7.4%; SiO <sub>2</sub> , 7.47%; K, 0.2%; Na, 0.03%; Fe-7.4 ppm; Al <sub>2</sub> O <sub>3</sub> , 6.3 ppm; sulfate, 278 ppm; Ba, 174 ppm; Sr, 804 ppm; Zn, 10 ppm; P., 0.02%; Mn, 172 ppm
6	Nano Ultra	SMTET Eco-technologies Co., Ltd., Taiwan	organic matter, 5.5%; Nitrogen, 10%; P <sub>2</sub> O <sub>5</sub> , 9%; K <sub>2</sub> O, 14%; P <sub>2</sub> O <sub>5</sub> , 8%; K <sub>2</sub> O, 14%; MgO, 3%
7	Nano-Micro Nutrient (EcoStar)	Shan Maw Myae Trading Co., Ltd., India	Zn, 6%; Fe, 6%+; EDTA Mo, 0.05%; B, 2%; Mn, 5%+; AMINOS, 5%; Cu, 1%

8	Nano Max NPK Fertilizer	JU Agri Sciences Pvt. Ltd., Janakpuri, New Delhi, India	Multiple organic acids chelated with major nutrients, organic carbon, vitamins, organic micronutrients/trace elements, amino acids, and probiotic
9	TAG NANO (NPK, PhoS, Zinc, POTASH, Cal, etc.) fertilizers	Tropical Agrosystem India (P) Ltd., India	Protein-lacto-gluconate chelated with micronutrients, vitamins, probiotics, seaweed extracts, and humic acid
10	Nano Green	Nano Green Sciences, Inc., India	Extracts of corn, grain, soybeans, potatoes, coconut, and palm
11	Geolife Nano Fertilizer Combi	GeolifeAgritech India Pvt. Ltd.	Zn + Mn + Cu + Fe + Mg 16.6+3.8+3.8 %.
12	IFFCO nano nitrogen, IFFCO nano zinc, IFFCO nano copper	IFFCO India	-
13	Geolife NPK, Nano fert	GeolifeAgritech India Pvt. Ltd.	19-19-19 Water Soluble Fertilizer
14	Master Nano Chitosan Organic Fertilizer	PannarajIntertrade, Thailand	Water soluble Liquid Chitosan Organic Acid and Carboxylic Salicylate Acids Phenolic compounds
15	Nano-Gro™	Agro Nanotechnology Corp., FL, United States	Zeolite
16	Nano-Ag Answer®	Urth Agriculture, CA, United States	NPK = <b>1.0 - 0.1 - 5.5</b>

- 1. Potential Ways of Nanofertilizer Uptake and Translocation in Plants:** Nanofertilizers are meant to interact with and be absorbed by root hairs when they are given to soil. Furthermore, it is thought that the nanofertilizer will be transported to all parts of the plant after reaching root epidermal tissues as well as deep xylem vessels[11]. Nanofertilizers are intended to interact with stomatal openings and microscopic pores in the epidermal tissue when they are administered through a foliar spray. To reach the phloem tissue, they start from where they enter and proceed deeply into the leaves' tissue. Then, they are moving throughout the entire plant from the phloem [12][13].
- 2. Application Strategies for Nanofertilizers:** There are three different approaches to apply nanofertilizers, which are explained below:
  - **In Soil:** Nanofertilizers can be added to soil by mixing solid nanoparticles before cultivation or by adding them to irrigation water during irrigation.

- **Seed Priming:** Before being planted in the ground, seeds are immersed in an emulsion containing nanoparticles. This technique was discovered to be most effective for dormant seeds[13].
- **Foliar spray:** When plants are in the seedling or early vegetative stages, foliar parts of the plants are sprayed with nanoemulsions of nanofertilizers[13].

Several studies revealed that foliar application is recommended for nanofertilizer application to plants, as seed priming can be toxic and cause seed abortion. Soil incorporation may not achieve desired results due to soil microflora degrading the nanofertilizers[13].



**Figure 1:** The schematic representation of Nanofertilizer’s potential benefits along with its mode of action

**3. Macronutrient Nanofertilizers:** Macronutrient nanofertilizers supply the plant with significant amounts of macronutrients like nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) [14]. By the year 2050, it is predicted that 265 million tons of macronutrient fertilizer will be required [15]. In comparison to conventional fertilizers, nanoparticles are more effective at releasing nutrients in a controlled manner due to their great penetration capacity and large surface area. In light of these facts, macronutrients are being used to produce nanofertilizers that have the capacity to release nutrients gradually or under regulated conditions.

The nanofertilizers have the ability to deliver nutrients gradually or under regulated conditions from macronutrients. For instance, [16] created a nitrogen slow-release nanofertilizer from urea-modified hydroxyapatite and assessed its efficiency.

Investigations revealed that although the nitrogen release from the produced nanofertilizer (urea-hydroxyapatite nanocomposite) started off quickly, it slowed down with time and persisted until 60 days after its application. At up to 50% less concentration than conventional urea fertilizer, this nitrogen nanofertilizer application has been shown to boost the production of rice.

- 4. Micronutrient Nanofertilizers:** Micronutrient nanofertilizers refer to fertilizers that give plants micronutrients, or substances that they only require in trace amounts yet are critical to their growth and metabolism [15][14]. Zinc (Zn), boron (B), iron (Fe), manganese (Mn), and copper (Cu) are the most significant micronutrients. According to [17], maize plants treated with zinc oxide (ZnO) nanoparticles had higher shoot height as well as dry weight than untreated ones. In addition, [18] found that ZnO nanoparticles (particle size: 25nm) were applied as a foliar spray on maize, and this improved maize growth, yield, and Zn content in the produced grains when compared to maize plants treated with regular ZnSO<sub>4</sub>.
- 5. Non-nutrient Nanofertilizers:** The special class of nanoparticles potentially has a positive impact on plants but that is not classified as plant nutrients. CNTs, chitosan (Cs), cerium (IV) oxide (CeO<sub>2</sub>), silicon dioxide (SiO<sub>2</sub>), and titanium dioxide (TiO<sub>2</sub>) represent the majority of these types of nanoparticles. Even though they are not of the nutritional requirement to the plant, they can nonetheless increase production and growth [15]. Date palm (*Phoenix dactylifera*) shoot length was shown to be increased by application of CNTs at 0.05–0.1 mg/L [19] and tobacco plant growth was observed to be enhanced at 5-500 mg/L [20]. Seed germination, plant growth, photosynthesis, and crop yield have all been improved by the application of Cs nanoparticles [15].

## 6. Advantages of Nanofertilizers

The following are the advantages of nanofertilizers:

- Reduces the cost of production and the requirement for fertilizers.
  - When used in soil, it minimizes nutrient loss due to soil drainage and leakage.
  - Synthesis can be carried out sustainably.
  - Enhanced plant nutrient uptake and regulated release of nutrients
  - Improved soil quality and nutrient availability.
  - Minimal toxic and adverse effects, particularly when given in low quantities.
  - Being able to maintain the value of output.
- 7. Limitations of Nanofertilizers:** Nanofertilizers have shown promise in improving crop productivity, but their deliberate introduction may lead to unintended nonreversible results and environmental and health issues. The phytotoxicity of nanomaterials is a concern, as plants react in a dose-dependent manner to different nanomaterials. Therefore, it is crucial to evaluate the advantages and limitations of nanofertilizers before market implementation [14]. Nanomaterials, due to their small size and surface area, are highly reactive, raising safety concerns for farm workers exposed to xenobiotics [21]. Examining the efficacy and effectiveness of these new fertilizers is crucial for sustainable agriculture,

as they face challenges in transport, toxicity, availability, and environmental consequences [21][14].

Some Studies have shown the phytotoxic effects of nanoparticles on plants, which depend on species, application mode, exposure time, and concentration. Understanding the toxicity of each nanoparticle is crucial for understanding nanofertilizer translocation, interactions with soil or compounds, and accumulation in plant tissues [14].

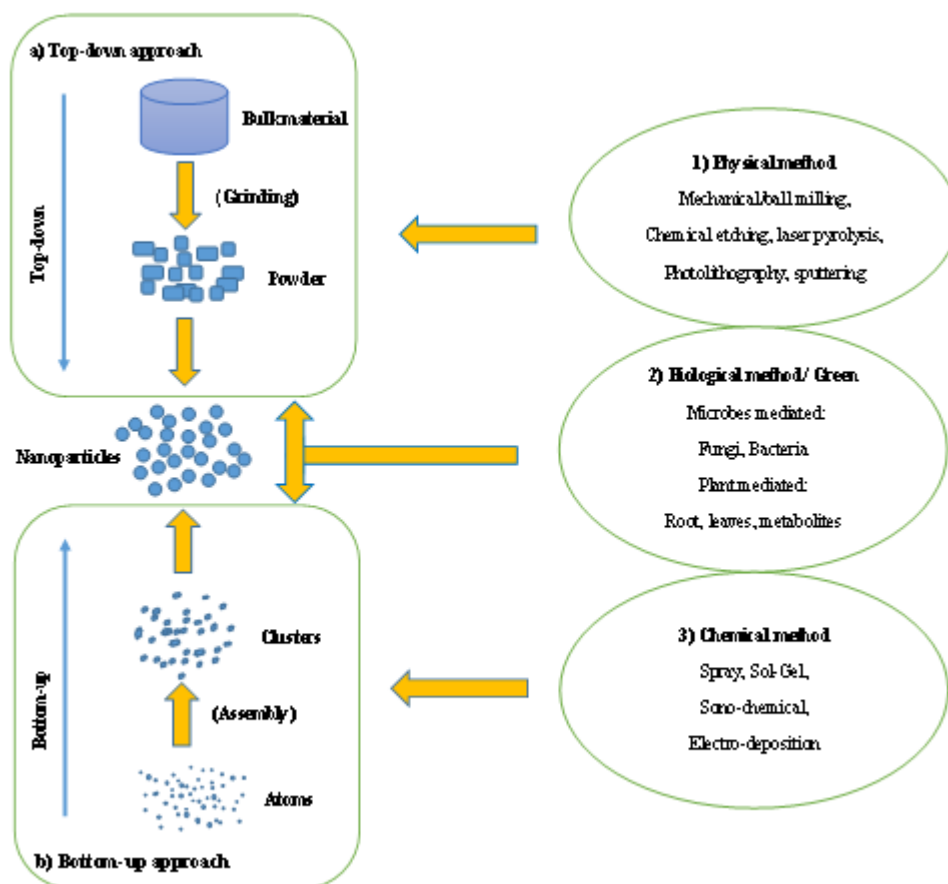
## VII. SYNTHESIS OF NANOMATERIALS

The top-down (Figure 2a) and bottom-up (Figure 2b) approaches represent the two principal methods to synthesize nonmaterial's. A majority of investigators select bottom-up approaches which employ wet-chemical or biological means over expensive, time and energy-intensive top-down physical methods. The bottom-up approach uses physical, chemical, and biological means, such as spray, sonochemical, vapor deposition, microwave, photochemical, chemical and electrochemical deposition, sol-gel, atomic and molecular condensation, laser pyrolysis, etc. Top-down methods employ physical means, such as mechanical/ball milling, chemical etching, photolithography, sputtering, etc.

The biological method is a green synthesis method (Figure 2) that uses eco-friendly materials and aqueous solvents, saves time and energy, and is cost-effective, sustainable, and non-toxic. It aims to reduce environmental and human risks associated with other methods and provides nanomaterials that meet the needs of the present century. Plants are used for nanomaterial fabrication, as they contain components like flavonoids, phenolics, terpenoids, carbohydrates, proteins, saponins, and acids (Figure 2). These biocomponents act as organic ligands, reducing bulk metals to nanoparticulate forms. This method offers nanoparticles with small sizes, eco-friendliness, low toxicity, simple reaction procedures, and enhanced surface morphologies, making it an attractive option for various applications.

### 1. Top-Down Approach

- **High-pressure homogenization:** High-pressure nanosizing techniques use shear stress and pressure to achieve uniform nano-size distribution [22]. Studies show a linear relationship between particle size reduction and applied pressure. Peanut protein homogenization increases hydrolysis with pressure from 0.1 to 80 MPa. High-speed stirring, consolidation, deformation, and densification are further top-down nanosizing methods [23].
- **Milling:** Milling involves mechanical force to reduce large materials to small particles, reducing them to nanoscale sizes at low temperatures. The ball mill is the most common type, using beads at high speed to interact with coarse materials in a chamber. The reduction in particle size is controlled by revolutions per minute and beads' size [24]. However, disadvantages include high energy, contamination, and ineffectiveness with moist or wet samples. The wet milling process, similar to dry milling, is applied to starchy and colloidal samples, primarily used for corn.



**Figure 2:** The schematic representation of nanoparticles a) Top-Down approach which includes physical and biological methods; b) Bottom-Up approach includes chemical and biological methods

## 2. Bottom-Up Approach

- **Emulsification:** Emulsification is a technique for encapsulating bioactive compounds in aqueous solutions, producing nanoemulsions with droplets ranging from 50 to 1000 nm. It is primarily used for high concentrations of oil-soluble food supplements, lipophilic active ingredients like plant sterols and carotenoid, and hydrophilic agents like polyphenols [22].
- **Nanoprecipitation:** Nanoprecipitation, also known as solvent displacement, involves precipitating polymers from organic solutions and diffusing solvents in an aqueous medium. This technique forms nanospheres and nanocapsules, improving bioavailability, bioactivity, and chemical stability of active compounds [22].
- **Nanoencapsulation:** Nanoencapsulation is a bottom-up technique used in the agri-food sector to package active ingredients like synthesized nanoparticles into a matrix or shell [22]. The core space within the matrix protects the encapsulated nanoparticles and ensures controlled delivery to target sites. This process is used in the food industry for flavoring agents, sweeteners, acidulants, colorants, preservatives, and

probiotics. In agriculture, nanoencapsulation applications include herbicides, insecticides, fertilizers, pheromones, pesticides, and microbicides for precision farming and increased productivity.

- **Coacervation:** Coacervation is a liquid-liquid separation technique for separating polyelectrolytes from a solution, forming coacervates around the active compound. It is used for masking odors, controlling protein release, biocompatibility, and biodegradation [22].

## VIII. NANOTECHNOLOGY IN PLANT PROTECTION

The production of food on a worldwide scale is severely impacted by a variety of abiotic and biotic stresses. Various conventional (artificial chemicals) and non-conventional (mixtures of natural combinations) approaches have been used to regulate biotic and abiotic stresses, but none have been completely effective. But multiple research projects on crop development have demonstrated how crucial nanomaterials are for plants' response to biotic and abiotic stresses and for improving soil nutrient status [25].

1. **Protection against Biotic Stresses:** Pest and disease management is a significant challenge for the agriculture industry, with synthetic chemicals being the most widely used solution. Nanopesticides, designed to target specific infection stages and release the right amount of chemicals, can reduce environmental pollution and degradation while enabling effective control measures. Nanomaterials possess properties like thermal stability, solubility, biodegradability, permeability, and slow release of active ingredients. Mesoporous silica nanoparticles protect pesticides from photodegradation, while gold and iron oxide nanoparticles have the potential for plant protection, but further studies are needed to confirm their effectiveness[24].

According to several studies, nanoparticles have antibacterial action against a variety of diseases. Plant diseases and crop pests can be directly inhibited by Mg, Ag, TiO<sub>2</sub>, and ZnO nanoparticles through a variety of antimicrobial activity pathways[26]. MgO nanoparticle suspension applied to tomato roots considerably decreased the occurrence of bacterial wilt disease. The finding has been associated with the activation of systemic resistance and stimulation of ROS generation, likely due to the expression of defense-related genes involved in systemic resistance. [23] reported the effective management of anthracnose pathogen (*Colletotrichumgloeosporioides*) strains in avocado and papaya were improved by ZnO and MgO nanomaterials and their combinations. By stimulating spore vacuolar expansion, these nanomaterials drastically reduced conidia germination, resulting in hyphae deformation. The fungal pathogen eventually died as a result of the inhibition of sporulation. MgO's anti-fungal action increased with crystallite size when applied to isolates from papaya (*Carica papaya*) plants, but it had no effect on isolates from avocado (*Perseaamericana*) trees. Nanomaterials possess antimicrobial and antifungal properties, making them potential for developing novel pesticides for crop protection in agriculture. Nanopesticides are composed of small particles with beneficial properties, such as low viscosity, small size, stable kinetics, optical transparency, biodegradability, permeability, and large surface area. These properties increase wet ability and dispersion, mitigating pesticide runoff, and reducing the application of large

quantities of pesticides. Delivery mechanisms like nanoencapsulates, nanocontainers, nanocages, and nanoemulsions have been investigated for effective pest and disease control [27].

- 2. Protection against Abiotic Stresses:** The effectiveness of nanoparticles against abiotic stresses has drawn considerable interest and has been extensively studied (Table 2). Drought, salinity, radiation, wounding, temperature, hypoxia, and metal toxicity are the primary abiotic stresses. Crop growth and productivity are decreased by these abiotic stresses [15] [28]. Numerous studies provided evidence that the use of NPs could influence a plant's growth and development, assist in coping with abiotic stresses, and stimulate certain biochemical pathways associated with the production of bioactive compounds like antioxidants [29]. The list of nanomaterials with their effect on different abiotic stresses and their response in plants have been mentioned in following (Table 2).

**Table 2: List of nanomaterials with their effect on abiotic stress response in Plants**

Sr. No.	Type of stress	Nano-material	Crop improvement	References
1	Drought	ZnO	Root length, fresh and dry weight, and seed residual fresh and dry weight all were increased.	[30]
2	Heat	TiO <sub>2</sub>	Increased the rate of transpiration, conductance to water, and net photosynthetic rate of tomato leaves	[31]
3	Cold	TiO <sub>2</sub>	Increased antioxidant enzyme activity decreased levels of oxidative stress and electrolyte leakage in chickpea seedlings	[32]
4	Drought	Fe	Reduced effects of drought stress on yield components and enhanced safflower oil content	[33]
5	Flooding	Ag	Increased production of proteins involved in metabolism, cell division, and organization that enhanced the soybean growth	[34]
6	Salinity	SiO <sub>2</sub>	An increase in the faba bean's growth, germination, yield, and antioxidant enzyme activity	[35]
7	Cold	Ag	Enhanced antioxidant activity-promoting gene expression in <i>Arabidopsis thaliana</i>	[36]
8	Salinity	K <sub>2</sub> SO <sub>4</sub>	Enhanced Alfalfa growth and physiological response by increasing proline content, catalase, and antioxidant enzymatic activities and reducing electrolyte leakage	[37]
9	Salinity	ZnO	Enhanced growth of stressed plants by stimulating photosynthetic levels, antioxidant enzymes activities and organic solutes.	[38]



10	Salinity	CeO <sub>2</sub>	Enhanced photosynthesis in soybean and regulated water use efficiency	[39]
11	UV-B	Si	Increased antioxidant synthesis in wheat seedlings to reduce oxidative stress through the NO-mediated route.	[11]
12	Salinity	SiO <sub>2</sub>	The increase in plant height (cm), leaves per plant (fresh and dry weights), fruits per plant (number, mean weight, length, and yield, in kg), and total yield	[10]
13	Drought	Zn and Cu	Increased antioxidant enzymes activity, increased water content and stabilized photosynthesis in wheat leaves	[40]
14	Drought	SiO <sub>2</sub>	Increased relative water content, yield and enhanced leaf greenness.	[41]
15	Heat	Ag	Improves plant root length, shoot length, root number, FW, DW, and protects wheat plants against heat stress	[42]
16	Chilling	Ag	Increased seedling height, net photosynthesis, fresh and dry weight	[43]
17	Salinity	Ag	Enhanced germination percentage and shoot length	[44]

- **Salinity Stress:** Excessive salt content in soil inhibits crop growth, affecting over 20% of cultivated land. This negatively affects plants, including reactive oxygen species, increased osmotic stress, and physiological and morphological changes. [45]

Evaluated the effect of silicon fertilizer and silicon nanoparticles during salt stress perfusion and as a result, basil (*Ocimum basilicum*) showed improved growth and development accompanied by an increase in chlorophyll and proline levels. The most prevalent macro-mineral element in soil is silicon, and silicon ions can help crops cope with a variety of stresses. Application of Si ions and silica NPs to rice indicates enhanced osmolyte formation and antioxidant defense system activation [46][28].

- **Drought Stress:** Drought conditions are caused by high temperatures, low rainfall, dry wind, and high light intensity, which affect plant growth and development. Nanoparticles are reported to improve tolerance to drought stress by reducing water loss and enhancing plant growth [29].

Drought causes defects in plants, including reduced leaf size, stem extension, root proliferation, and water relations. Pre-treatment with nanoparticles (NPs) improves water content, photosynthesis, membrane electrolyte leakage channel, chlorophyll, carotenoid, carbohydrate, and proline, which act as drought stress barriers[29]. The addition of Nanoparticles in a plant growth medium activates a variety of defense mechanisms to safeguard the plant. For example, it lessens the permeability of the plasma wall of leaf cells, which prevents lipid peroxidation. Additionally, it shields the plant's cell wall from heat and drought stress.

## **IX. FUTURE OF NANOTECHNOLOGY IN PLANT IMPROVEMENT**

Sustainable agriculture and food availability are crucial for nutrient security and sustainable development. Nanotechnology can improve plant nutrient availability and minimize soil losses. Nanomaterials enhance crop production and nutrition but may also have toxic effects on the environment when used in applications like fertilizers, pesticides, and food packaging. Understanding this phenomenon is essential for developing new technologies for soil improvement and crop production. New developments in eco-friendly materials for nanoagriculture offer potential benefits, but the effects of toxic materials on ecosystems remain uncertain. To address this, researchers are focusing on using biological organisms, which possess special functional groups that affect material transformation and have capping and stabilizing effects. This shift towards sustainable agriculture and green chemistry aligns with the principles of nanotechnology. This novel technology in agriculture offers benefits such as soil reclamation, herb and pest control, macro- and micronutrient supply, nutrient absorption, food security, nanofood delivery, and food packaging. It focuses on the overall development of the agricultural sector, from the field to the well-being of individuals and organisms that rely on crops. While it is gaining attention, much work remains to be done. Smart technology in agriculture uses gold and silver stripes nanobarcodes in crop and food packaging, revealing product information, addressing concerns about nanoproducts, and improving crop improvement. Nano-graphene oxide in biosensing has shown a very promising method of detecting aflatoxin in food as well as a general aptamer-based amplification platform for the investigation of a variety of mycotoxins, by substituting the aflatoxin aptamer with aptamers for other targets.

## **X. BIOSAFETY: NANOMATERIALS IN AGRICULTURE**

Nanoparticles made of ZnO, TiO<sub>2</sub>, Fe<sub>3</sub>O<sub>4</sub>, CeO<sub>2</sub>, Au, Ag, Cu, and Fe are among the materials that are frequently investigated. They have an impact on soil health and plant nutrient fortification in a number of different ways. Nanomaterials' safety depends on the synthesis method used, with chemically, physically, and biologically synthesized nanomaterials being more toxic. Chemically-synthesized nanoparticles pose greater toxicity due to their slow release of chemical agents. Biologically-engineered nanomaterials are more biocompatible and safer for the environment and organisms. Nanomaterials' properties vary due to different methods and reaction conditions, resulting in contrasting results. Factors such as particle sizes and fabrication materials affect their behavior and toxicity. To ensure safety and sustainability, there is a trend towards biological methods for nanomaterial synthesis, as these materials significantly affect nanoparticles. Bionanomaterials are composed of biomolecules that may be harmful and behave differently, making it crucial to observe individual nanomaterials individually. There is no doubt that the use of nanomaterials to improve plant nutrition and crop production is gaining popularity, but there also has to be more focus on the safety of these substances given the fine line between toxicity and deficiency. We cannot completely rule out the risks associated with the use of nanotechnology in agriculture, notwithstanding the positive achievements in this area. Modern research should invest more in assessing the safety of materials in order to improve their preparation, characterization, and general application criteria since it has accepted this technology as a means of unmatched progress.

## XI. CONCLUSION

Nanotechnology and nanostructures are increasingly being used to improve agricultural practices, improving nutrient absorption, yield, nutritional quality, and plant disease management. It remains a promising alternative to the agricultural sector, offering advantages such as manipulative ability, high carrier system use, bioavailability, and low toxicity. To make this field more profitable, plant-mediated biological methods of synthesis should be explored using waste vegetables, extracts, flowers, barks, roots, fruit peels, and leather cuttings. The use of microbial pesticides and chemical fertilizers poses significant threats to food safety, making conventional farming practices ineffective. Nano-based fertilizers can also improve environmental conditions and monitoring systems for sustainable agriculture. Nanotechnology can enhance crop biology, yields, and nutritional values. Nano-based products like pesticides, insecticides, and herbicides can manage pests, insects, and weeds.

Regulations on nano-products should protect the environment and public health. Nanotechnology industries should provide product information for their nanomaterials. Despite potential challenges, it is now time to introduce nanomaterials in crop production, nursery stages, and land preparation. This could improve nutritional health, sanitation, food security, sustainability, and the environment; particularly in developing countries. Further research is needed to develop cost-effective, safe, and environmentally friendly nanomaterials. It is crucial to raise public awareness about the risks associated with nanotechnology and promote responsible agricultural practices.

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