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Advancements in Nanofertilizer Technology: Design, Applications, and Agricultural Benefits

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Abstract : This paper aims to explore nanotechnology as a potential solution to the problems associated with the use of conventional fertilizers in agriculture. The article aims to review the development, formulation, and utilization of nanofertilizers (NFs) with special reference to enhancing nutrient acquisition efficiency and minimizing environmental effects. The positive and negative impacts of nanoparticles (NPs) on plants and agriculture are explored in detail. Although nanofertilizers promote growth, photosynthesis, and stress tolerance in plants, there are controversies over the cytotoxicity and ability to induce oxidative stress in the plants and biosphere. This paper delves into the recent development in nanofertilizers, controlled nutrient release, and their targeted delivery. Furthermore, it outlines areas for further research and possible challenges of NF adoption in the agriculture industry. More attention should be paid to the improvement of NF structures, reduction in their toxicity, and sustainable synthesis strategies for better performance of NFs.

IndexTerms **- Nanofertilizers (NFs), nanoparticles, agriculture, targeted delivery, nutrient release, environmental sustainability.**

I. INTRODUCTION

Eco-friendly technologies have been increasingly used in agriculture as a replacement for conventional fertilizers and pesticides lately. The disadvantages of traditional fertilizer usage in agriculture can be addressed by nanotechnology. Consequently, the application of nanoparticles (NPs) for agricultural purposes is rapidly growing. This review offers a distinct viewpoint on recent developments in nanoparticles composition and design for use as nanofertilizers along with various agricultural applications. Recent studies on nanoparticle–plant interactions and their impact on crop yields are also described in this review.

Due to their extremely reactive nature, penetration ability into the epidermis, and ability to release and disperse nutrients slowly, nanofertilizers are crucial for reducing the consumption of inorganic fertilizers as well as their negative environmental impacts. Abiotic stresses and heavy-metal poisoning may also be lessened with their assistance. However, there have been reports of nanoparticles' harmful effects in several plants as a result of their accumulation in organelles and on surface cells, which causes oxidative stress (El-Saadony et al., 2021). According to one study, for instance, NPs have negative impacts on plant growth, photosynthesis performance, and chlorophyll production. Based on the type of nanoparticles used, concentration, and species of plants, NP impacts can be either positive or negative (Goswami and Mathur, 2019).As copper oxide NPs enter cells and their various regions, they have been shown to possess cytotoxicity and genotoxic impacts (Moschini et al., 2013). According to a different report, NPs have the ability to enter cells and interfere with the ETS or electron-transport system cycle in the mitochondria and chloroplasts, which may trigger an oxidative spike by increasing reactive oxygen species (ROS) (Hossain et al., 2015). Metals and metal-based nanoparticles can induce oxidative stress in a variety of plant varieties. Reactive oxygen species cause oxidative injury to mitochondrial and chloroplast DNA, which alters the encoded protein and causes the designated proteins to malfunction and become completely inactive (Atha et al., 2012). AgNP exposure to Ricinus communis seeds enhances the production of ROS, which is linked to the defense system of antioxidants (phenolic acids, peroxidase activity, and the enzyme superoxide dismutase) (Belava et al., 2017). ZnO nanoparticles significantly reduce ryegrass biomass, resulting in root-tip shrinking and collapsing or extensively vacuolated root epidermis and cortex cells. Both the root surface, apoplast, and protoplast of the stele and root endodermis were found to contain individual zinc oxide nanoparticles. Zinc translocation factor from root to shoot stayed low with decreased ZnO NP treatment (Lin and Xing, 2008). Unaltered plants have been found to accumulate CeO_2 NPs, which could be harmful to human well-being (Morales et al., 2013). The detrimental consequences of metal oxide nanoparticles on soil bacterial populations were documented in a study conducted on grassland soil (Ge et al., 2011). However, compared to the actual ecosystem today, these numbers are incredibly high. Nevertheless, investigating how manufactured nanoparticles affect the rhizosphere microbiota and implementing strategies to counteract their possible negative impacts on agricultural soils are necessary. One intriguing study used Fe3O4@PW-αCFs (renewable) to act as supermagnetic bioadsorbent to remove massive amounts of engineered nanomaterials, such as ZnO, CuO, and CoO, from a variety of actual wastewater specimens in an easy, inexpensive, and practically feasible wastewater treatment method (Kadam et al., 2019). Furthermore, details regarding the drawbacks and prospects of employing nanofertilizers in place of traditional fertilizers have also been covered.

Various NPs, such as metal oxides, carbon-based NPs, and various other nanoporous compounds, may be combined to create nanofertilizers, based on their compositional characteristics (Liu and Lal, 2015). Physical, chemical, or biological methods may be

employed to manufacture them (Zulfiqar et al., 2019). Rather than using the physical and chemical approaches presently used to make nano-products, nanofertilizers may also be manufactured using a novel technology that uses clean, non-dangerous, and exceptionally ecologically friendly processes, like bio-fabrication and green nanotechnology (Saratale et al., 2018). Numerous benefits are provided by nanofertilizers, including the regulated and progressive distribution of different micronutrients and macronutrients for plants at certain concentrations, as well as enhanced surface areas and suitable sizes (Usman et al., 2020). These nanofertilizers release nutrients into the soil, and plants react to those nutrients. Depending on the particular nutrient sources, various types of nanofertilizers, such as nanomaterial-enhanced fertilizers and micronutrient/macronutrient fertilizers may be produced (Duhan et al., 2017). Enhancements in solubility, phytoavailability, dispersion of non-soluble minerals, and targeted delivery to reduce nutrient loss are credited to these nanofertilizers (Prasad et al., 2017). Various proteins, coenzymes, vitamins, purines, and pigments responsible for photosynthesis and plant respiratory processes are also influenced by them (Jakiene et al., 2015).

This paper covers an innovative summary of current advancements in the varieties, modes of application, and possible effects on agricultural crops using nanoparticles utilized as nanofertilizers. In addition to highlighting the present limitations and potential challenges associated with the extensive use of NPs prior to field applications, the primary focus revolves around the possible advantages of nanofertilizers.

II. Advancements in Nanofertilizer Technology

The management of crop nutrients and soil fertility will be the greatest challenge in coming decades because of the widespread application of chemical fertilizers with current agricultural techniques. Conventional fertilizers typically cause substantial water body loss, reduced agricultural nutrient output, and adverse environmental effects. Therefore, in contrast to synthetic fertilizers, a novel and sustainable fertilizer technique is needed to increase all productivity in our agricultural system. In order to provide sustainable crop yields and safeguard the environment by using sophisticated pesticide delivery, the use of nanohybrid structures, including nanofertilizers, has recently attracted a lot of attention (Raliya et al., 2017). Scientists worldwide have been attracted toengineered nanohybrid constructs like nanofertilizers due to their adjustable physicochemical properties and efficient functional assembly. Accordingly, nanotechnology is transforming the manufacturing and designing of different materials through the modification of their properties in order to meet various demands and needs. Comparing conventional chemical compost, the use of nanofertilizers has been shown to increase crop yield (DeRosa et al., 2010). Additionally, novel attempts have been made to enhance the way nanofertilizers react with their surroundings so as to monitor moisture, temperature, humidity, pH, and other factors (Duran and Marcato, 2013).A potential alternative approach to supplying crops with nutrition in a controlled way, nano-biotechnology has gained popularity in this regard and has the ability to transform agricultural practices. Furthermore, by improving the abiotic stress tolerance as well as crop output, nanofertilizers constructed from engineered nanoparticles may aid in the regulation of crop nutrition (Al Mamun et al., 2021). Figure 1 illustrates thedesign, interactions,and effects of NFs on food plants according to the most recent studies.

2.1 Manufacture and Design of NFs

One essential element of the nanotechnological fertilizer approach is the use of nutrient-rich nanoparticles. Nanomaterials may be created using both chemical and physical methods. These two strategies are further divided into three categories: chemical, biological, and physical. The chemical strategy focuses on synthesizing NPs chemically, whereas the physical method and biosynthesis deal with the physical process of synthesis. A lot of research have developed and employed nanomaterials as nanofertilizers (Abbasifar et al., 2020; Cota-Ruiz et al., 2020; de Franca et al., 2020; Ramirez et al., 2020).Common elements may be nanostructured and utilized as nanofertilizers, including sodium (Na), zeolites, iron (Fe), silver (Ag), silica (Si), calcium (Ca), potassium (K), carbon (C), copper (Cu), nitrogen (N), carbon (C), zinc (Zn), aluminum (Al), magnesium (Mg), and manganese (Mn), The production of nanofertilizers also uses diverse materials derived from plants, for instance banana peels (Sharma et al., 2014) or grape plant substrates (Hussein et al., 2019). Over 50 minerals make up natural zeolite that has lately been transformed into nanofertilizers because it is inexpensive and widely available (Eroglu et al., 2017). To address a particular nutritional need in plants, nanofertilizers might be developed or customized. This is made feasible by the ability to arrange atoms on NP surfaces to achieve desired characteristics (Elemike et al., 2019). The following techniques can be used to prepare nanofertilizers:

I. Encapsulation in nanoparticulate
II. Absorption on NPs.
III. Entrapment of polymeric NPs.
IV. Attachment to NPs.

The method most frequently used to create nanofertilizers using nanomaterials is nutrient encapsulation. In the past few years, certain nutrients have been found in nanoporous compounds in which a thin layer of nanoscale polymer has been applied. Nitrogen, phosphorus, and potassium availability within the root zone can be increased by encapsulating an efficient microorganism, e.g., bacteria or fungi(Bose, 2020). Finally, the word "nanofertilizers" describes a nanomaterial that is either a carrier of a plant nutrient or a plant macro or micronutrient. Moreover, nanofertilizers comprise nutrients that are either encapsulated or coated in nanomaterials. They may be produced chemically, mechanically, or biologically from green synthesis, i.e., plant extracts or different synthetic substances, also known as "modified synthetic fertilizers" (Singh and Kumar, 2017).

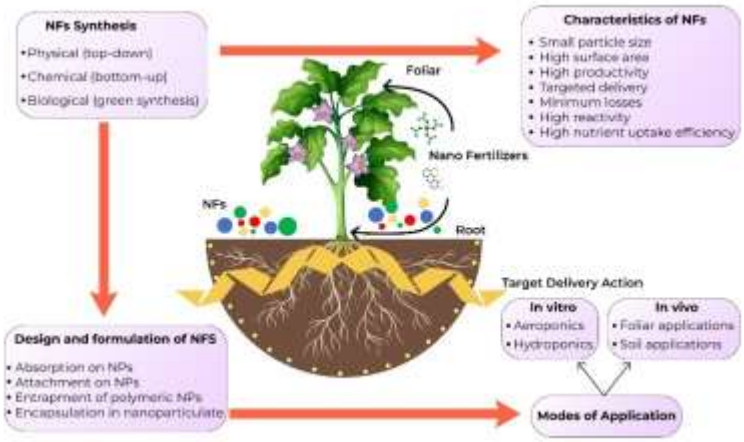


Figure 1 Design, interactions, and effects of nanofertilizers (NFs) on food crops. This diagram summarizes NF synthesis pathways, interactions with root epidermis, translocation pathways, and physiological responses including nutrient absorption and stress mitigation (Adapted from Zahra et al., 2022).

Based on the method of their production, nanofertilizers are categorized into three types: (a) "nanoscale fertilizers" that are insignificant in size like nanoparticles and are comparable to traditional fertilizers; (b) "nanoscale additive fertilizers" that are ordinary fertilizers with extra nanomaterial; and (c) "nanoscale coating fertilizers", that involve encasing nutrients within nanofilms or introducing them into the minute pores of a host substance (Mastronardi et al., 2015). Nutrient release has been regulated by using nanocomposite structures that include encapsulated nutrients or nutrients embedded in the nanopores inside the host substance, e.g., clays (Golbashy et al., 2017; Kottegoda etal., 2017; Borges et al., 2019).

2.2 Characteristic Features of NFs

To reduce nutrient losses, contemporary formulation-based nanofertilizer manufacturing improves the uptake of insoluble nutrients, their solubility, bioavailability, and the accessibility of particular nutrients (Prasad et al., 2017). According to one study, nanoparticles were produced utilizing a range of engineering approaches followed by encapsulation, having the necessary nutrients for increasing the effectiveness of target-specific uptake by plants (Zulfiqar et al., 2019). Better improved absorbability, chemical stability, greater surface tension, enhanced mobility, pH tolerance, and ionizing power are all requirements for nanofertilizers(Seleiman et al., 2020). According to reports (Usman et al., 2020), nanofertilizers may have a slow-release activity and give different macro or micronutrients to plant tissues at an increased surface area, specific concentrations, and appropriate size because of these promising qualities, as illustrated in Figure 2. The use of nanofertilizers may increase the efficiency of nutrient use, reduce the chemical burden on the soil, lower the application frequency, and mitigate the adverse impacts of traditional, bulky fertilizers. Put differently, the purpose of nanofertilizers is to improve the bioavailability of plant nutrients, the quality of the product, and soil fertility (Seleiman et al., 2020). Because of these features, nanofertilizers are highly appropriate for application in contemporary agricultural systems (Prasad et al., 2017, and Seleiman et al., 2020).

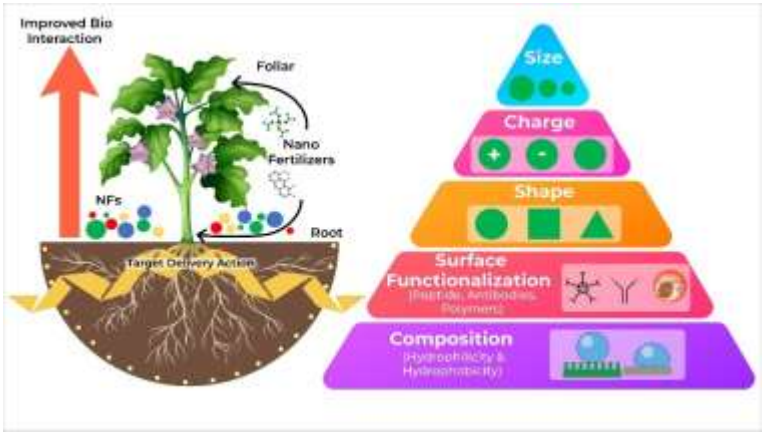


Figure 2: Characteristic features of nanofertilizers (NFs). This diagram illustrates key properties of nanofertilizers including increased surface area, enhanced solubility, slow and controlled nutrient release, pH tolerance, and ionizing capacity. These features improve nutrient uptake, reduce environmental losses, and optimize delivery efficiency in plant systems (Adapted from Zahra et al., 2022).

Due to their minuscule size, i.e., nanometers (Hussain et al., 2022), nanomaterials, like nanofertilizers, are more capable of absorbing and retaining nutrients than large, artificial chemical fertilizers. The increased surface area of nanofertilizers allows them

to absorb extra nutrients and disperse them evenly according to crop needs without causing any negative effects (Siddiqi and Husen, 2017). Reduced efficiency of nutritional absorption and nutrient loss via leaching, emissions of gases, volatilization, etc., are the main causes of the environmental destruction brought on by synthetic fertilizers (Dimkpa et al., 2015). Nonetheless, the gradual and even dispersion of essential nutrients from nanofertilizers lessens the negative environmental impacts.

According to research, the cell walls of plants that have pores of 5-20 nanometers in size serve as aself-defence barrier. Crucial nutrients, either supplied in the soil or applied to the leaf surfaces, are only produced by external compounds/agents that are shorter in diameter compared to plant cells and may penetrate through SELs or size exclusion limits (Al-Mamun et al., 2021). Furthermore, several other nanoparticles may penetrate and enhance genetic characteristics via coupling to build intracellular components in cell walls (Larue et al., 2012). When compared to traditional hydrophilic fertilizers, fertilizers aided by nanotechnology have shown exceptional transport properties through plant tissues with controlled movement. Silicon dioxide with sizes ranging from 50 to 200 nanometers has been found to pass through the Arabidopsis thaliana plant roots (Slomberg and Schoenfisch, 2012). The parenchyma of the wheat root was inaccessible to TiO2 nanoparticles having a diameter of 36–140 nanometers; nevertheless, nanoparticles having a diameter of 36 nanometers could penetrate the inhibitory structures in wheat and reach the other plant parts (Larue et al., 2012). Given their greater diameter compared with the root cell diameter, i.e., 6.6 nanometers, TiO2 nanoparticles of 30 nanometers failed to translocate when used on maize (Asli and Neumann, 2009). The entry of TiO2 nanoparticles into wheat crops has been tested in a different study, which found that some NPs penetrated the root cells whereas others failed to. The nanoparticles remained polydispersed with larger particles clumped together in the soil that prevented penetration while smaller particles (less than 20 nanometers) could pass through roots (Du et al., 2011). This implies that NF translocation and absorption in the plant system depend critically on particle size.

The NFs' surface charge also affects their absorption and distribution in plants like that of particle size (Lv et al., 2019). Mucilage (a sticky and viscous substance secreted by Arabidopsis thaliana roots), made it easier for positively charged Au nanoparticles (12 nanometers) to penetrate the roots whereas negatively charged Au nanoparticles of the same size, i.e., 12 nanometers, did not (Avellan et al., 2017).

2.3 Controlled Release and Targeted Delivery of NFs

Increasing the NUE of greenhouse and field crops is the primary way that nanofertilizers can promote environmentally friendly agriculture and raise total agricultural yield. NFs may deliver nutrients gradually and steadily, either on their own or as a combination of synthetic or organic fertilizers. Unlike synthetic fertilizers, which take 4-10 days for nutrient release, nanofertilizers achieve it in 40–50 days. The problems of volatilization and leaching cause the chemically manufactured urea fertilizers to rapidly lose over 70% of theirnitrogen concentration following field application, retaining only 20% for plant uptake (Kahrl et al., 2010). Lately, urea was encapsulated with hydroxyapatite nanoparticles to create nitrogen in the form of nanofertilizers, which slowed the release of nitrogen to crops. Likewise, using nanohybrid urea (an altered kind of hydroxyapatite) in rice fields can increase grain output at half the rate of regular urea and give off nitrogen as much as 12 times more slowly than synthetic urea. In recent years, urea has been coated or encapsulated with hydroxyl apatite nanoparticles to create N-nanofertilizers, which release nitrogen to plants gradually (Kottegoda et al., 2017). Phosphorus nanofertilizers aid in the direct uptake of phosphorus by plants, reducing phosphorus losses (Dwivedi et al., 2016).

By altering the outermost layer, nano-agrochemicals may be delivered precisely and released under control. Nanofertilizers significantly affect the growth and germination of seeds in the agricultural sector. Rapid penetration into the soil and root system allows them to improve the nutrient release, dry matter production, and chlorophyll generation, all of which accelerate plant growth (Suriyaprabha et al., 2012). The inherent aggregation ability of different nanomaterials lowers their effectiveness, thereby promoting the production of ROS (Abdelmonem et al., 2015). Polymers like polymethacrylic acid (PMAA), N-vinyl-2-pyrrolidone (PVP), poly (methyl methacrylate) (PMMA), polyethylene glycol (PEG), surfactants like gluconic acid and cellulose, and chemicals like chitosan and oleylamine, have been widely utilized for stabilizing in order to prevent agglomeration (Mwilu et al., 2013).

2.4 Application Modes

The application of nanofertilizers must preserve their potent attributes, including stability, targeted distribution, solubility, efficiency, time-controlled release, and reduced toxicity. The method, which they are applied for secure delivery and disposal,exerts the biggest influence on their efficacy and effect. There are several techniques for delivering NFs to plants that are discussed below.

2.4.1 In Vitro Techniques

Both hydroponics and aeroponics use soilless techniques. The roots of the plant remain in air while the solution of nutrients is repeatedly sprayed as a mist in aeroponics. This makes it simple to regulate the whole ecosystem close to the roots. Due to the high nutritional requirements for quick, sustainable growth, this technique is not commonly employed (Kalra et al., 2020). However, hydroponics—also referred to as the "solution culture" technique—uses inorganic salts that are naturally soluble. With particular consideration given to the solution volume, pH, and O2 availability, the plant roots are submerged in a rich solution of nutrients. Supportive elements like gravel, sand, etc. also have several commercial uses. At one end, the nutrient-rich solution gets released and the preceding solution is removed. Increased transpiration rates along with numerous pathogen attacks are drawbacks of this approach, that may lead to severe wilting of soil-based plants (Solanki et al., 2015).

2.4.2 In Vivo Techniques

Soil and foliar application currently represent two more subcategories of in vivo techniques.

In the foliar method, liquid fertilizers are sprayed onto the leaves for delivering micronutrients directly. This method is advantageous due to the shortening of time between the administration of NF and the absorption of nutrients by crops during their exponential growth period. It additionally enhances micronutrient uptake as mentioned earlier, unlike the soil application approach where micronutrients like copper, iron, and manganese Cu, Fe remain more saturated on the soil particles (Taiz and Zeiger, 2010).

Since stomata and leaf epidermal cells are involved in intake of nutrients, using NF application may have agronomic advantages. The amount of time that it requires for stomatal pores to widen needs to be taken into account because stomata is involved.

The foliar application of NPs in conjunction with nitrogen, potassium, and phosphorus was investigated. When Nanochitosan-NPK fertilizer was applied to the wheat crops, the harvest, crop, and mobilization indices all increased, yielding noteworthy outcomes. The foliar absorbance of the nanocomposite in watermelon showed similar outcomes (Wang et al., 2013). Likewise, foliar treatment of Au (gold) nanoparticles produced positive results in seed yield, diameter, as well as number of branches (Marzouk et al., 2019). Regarding the best foliar uptake, factors including working conditions such as water, gas, light, etc, plant species, and modes of nanoparticle distribution must be taken into account in conjunction with particle size (Birbaum et al., 2010).

Numerous factors, including crop phenology, rhizosphere activity, plant shape, size of NP, and acquaintance conditions, affect the soil application and NF uptake on the plant root. Prior to entering the vascular system of the plant, soil-applied NFs travel through several barriers after entering the root system via their surface. The first hurdle is the root's cuticle barrier, forming a composition with the cuticle covering of leaves. Nanoparticles penetrate into the root epidermis following entry into the cuticle. Once they enter the root epidermis, they have two routes to choose from: symplastic route or apoplastic route. The apoplastic method involves NFs translocating into intercellular spaces after first penetrating the wall pores of the cell (Lv et al., 2019).

Large nanofertilizers of more than 20 nanometers cannot adopt the apoplastic route because of the cell wall diameter, i.e., 5–20 nanometers. Nevertheless, NP-induced cell death can result in an increase in pore size. A significant obstacle in the apoplastic approach, nevertheless, involves the Casparian band, which prevents nanoparticles from entering directly into the vascular cylinder (Roppolo et al., 2011), but ZnO-NFs measuring 30 nanometers were discovered in the vascular system via a maize-cross root junction (Lv et al., 2015). Conversely, in the symplastic process, nanoparticles use the plasmodesmata route to move across cells (Rico et al., 2011). The middle cylinder allows nanoparticles to enter the aboveground section of the plants, and the distribution channel from the xylem follows (Larue et al., 2012). Researchers' experiments with nanofertilizers to increase crop development may pave the way for more ecologically friendly and sustainable agriculture (Abdel-Aziz et al., 2016).

III. Effects on the Agricultural System

For plants to grow and develop properly, both micro and macro nutrients are of equal importance. The absence of any of these nutrients might hinder the germination of seeds and impact on the growth of plants (Madan et al., 2016). However, too many of these nutrients might also slow down the crop's development. Getting adequate vital nutrients to satisfy the needs of fundamental cellular functions is challenging. For plants to finish their life cycles, they need an accurate and targeted delivery of nutrients. After being consumed by the plants, mineral nutrients serve a variety of purposes (Duhan et al., 2017). Enzymes, pigments, and proteins that participate in cellular metabolism and signaling are produced from these nutrients. These essential nutrients for plant development include the following: nitrogen, phosphorus, potassium, manganese, magnesium, oxygen, carbon, calcium, iron, boron, sulphur, chlorine, nickel, zinc, and Copper. Amongst these, the elements that the plant needs most are potassium, nitrogen, phosphorus, and magnesium. They may enter plants through the root system; however, they are incapable of being directly absorbed from the environment (Wang et al., 2016). The technical solution to nutrient deficiency problems has thus been the nanoscale sizes of NFs (Al-Mamun et al., 2021). Crop plants' nutritional value has generally increased due to nanomaterials (Wang et al., 2020). Substantially improved physicochemical properties of zinc oxide nanoparticles could make them a novel fertilizer that improves agricultural output and quality of food (Dimkpa et al., 2018, and Hou et al., 2018). Multiple investigations have documented how NPs improve plant development, plant growth, and seed germination. Many agricultural plants have been found to exhibit improved biomass, sugar, micronutrients, photosynthesis effectiveness, nitrogen, and total protein. These include Solanum lycopersicum (Faizan et al., 2018), Triticum aestivum (Zhang et al., 2017), Triticum aestivum (Zhang et al., 2017), Cucumis sativus (Kim et al., 2012), and Glycine max (Dimkpa et al., 2017). In a gel-based chambered culture of C. sativus, zinc oxide nanoparticles in a concentration of 1.00 mg/L enhanced root biomass with longer shoots in comparison with conventional zinc oxide treatments (Moghaddasi et al., 2017). Nevertheless, excessive quantities of these nanoparticles may also harm the plants.For instance, excessive levels of zinc oxide nanoparticles and the resulting derivatives, especially zinc chloride, in the soil can make plants toxic (Liu et al., 2015) and have an impact on photosynthetic efficiency, biochemical and physiological qualities, nutritional quality, yield features, growth, and seed germination (Du et al., 2011; Du et al., 2017; Zuverza-Mena et al., 2017). Table 2 provides a summary of recent research on the applications of nanofertilizers.

The degradation of land, nutritional deficiencies, low crop yields, leaching, and other issues associated with agriculture could all be resolved by nanotechnology (He et al., 2019). The large "surface-area-to-volume" ratio of NFs' nanostructure reportedly enables crops to take in nutrients slowly but sustainably as needed (Hossain et al., 2008, and Hussein et al., 2010). Additionally, NFs provide a number of benefits, such as improved crop yield, decreased nutrient loss, higher soil fertility, less pollution of the environment, and a sustainable home for microbes (Liu et al., 2006). To increase the supply of nutrients to plants, numerous researchers have combined hydroxyapatite and urea for the production of slow-release fertilizers (Xiong et al., 2018).

A sustainable agricultural system also uses nano-based fungicides, insecticides, herbicides, and pesticides as a replacement for nanofertilizers. By encasing them in an NP shell, nanopesticides address the drawbacks of traditional pesticides and render them exceptionally water soluble (Chaud et al., 2021). The effective application of nano-pesticides may raise crop yields. By employing nanocarriers, often known as "precision farming," which boosts crop output without harming the soil or water, these pesticides may be delivered precisely and with an extended-release time (He et al., 2019).

Research has shown that herbicides with nanotechnology can effectively kill weeds and boost crop production. Furthermore, nanoparticles enhanced the potency of certain herbicides like atrazine, triazine, and ametrine by about 84% when mixed with them (Rajput et al., 2021). In one study, Brassica juncea (mustard plant) was treated with atrazine-loaded polyepsilon-caprolactone nanocapsules, which produced better herbicidal performance than commercialized herbicides (Oliveira et al., 2015). To achieve pesticide-controlled delivery, silicon nanoparticles were also created and employed as nanocarriers (Cao et al., 2017). Furthermore,

herbicide dosages are reduced by nanoencapsulation (a more environmentally friendly technique) without sacrificing effectiveness. Because metal oxide NPs like copper oxide, titanium dioxide, and zinc oxide are naturally toxic, they have been widely applied to protect plants from pathogenic attacks (He et al., 2019).

Moreover, containerization of food, food preparation, processing, and development, food hygiene, longer shelf lives, and microbial detection in food are all significantly impacted by nanotechnology. In addition, the use of nanotechnology has improved the detection and utilization of crop traits, made gene sequencing easier, and modified plants' ability to respond to illnesses and environmental stressors (Neme et al., 2021).

IV. LIMITATIONS OF NF TECHNOLOGY

A key opportunity to curb the growing worldwide demand for food is creative agricultural development. Reduction in environmental degradation and responsible agricultural expansion are the two top priorities for effectively developing a beneficial crop-yield framework. Nonetheless, past experiences show that overuse of nanofertilizers harms both biological systems and ecosystems. While the traditional agricultural system benefits from the use of nanofertilizers, other researchers are concerned regarding the potential drawbacks. Since NPs are reactive in nature, they may interact with different elements of the environment and change their physicochemical characteristics. Toxicity may be caused by these altered nanofertilizers when they interact with soil constituents.The buildup of these nanofertilizers, however, can result in ROS generation, growth inhibition, and eventually death of cells.

Table 1 Summary of the types, applications, effects and risks associated with NFs

S.No	Type of NF	Mode/Method of Application	Observed Effects on Crops	Potential Risks
1	Copper Oxide (CuO) NPs	Soil	Improves enzyme activity, enhances stress tolerance	Genotoxic effects, disruption of ETS cycle
2	Zinc Oxide (ZnO) NPs	Foliar, Soil	Enhances biomass, root growth, and photosynthesis	Toxicity at high concentrations, root shrinkage
3	Carbon-based NFs	Foliar, Soil	Increases nutrient retention, enhances soil fertility	Unknown long-term environmental impact
4	Nanochitosan-NPK	Foliar	Improves yield, enhances nutrient mobilization	Stability issues, aggregation tendencies
5	Silver (Ag) NPs	Soil, Seed Coating	Increases ROS defense, promotes germination	Potential cytotoxicity, oxidative stress
6	Iron-based NFs	Soil, Hydroponic	Boosts chlorophyll content, enhances nitrogen fixation	Potential accumulation in edible parts
7	Hydroxyapatite-based NFs	Soil, Foliar	Slow nutrient release, improved phosphorus uptake	Limited large-scale testing

This buildup of nanofertilizers in food may be fatal to people. 15% of Ce4+ turned out to be converted into Ce3+ in a study that examined the CeO2 nanoparticles uptake and transportation in cucumber cultivars. The resultant compounds were then transferred to the phloem. It is necessary to assess these transported species' security issues because they may be hazardous to human health (Ma et al., 2017).

Overuse of nanofertilizers in farming operations may lead to unintended and lasting environmental problems. Since nanoparticles are reactive and unpredictable, there are also concerns regarding worker protection during manufacture and field use. As a result, it is essential to assess the hazards and determine the adverse consequences of these nanofertilizers, involving a life cycle assessment (Bernala et al., 2021). Furthermore, we must make sure that these NFs are solely employed at the optimal amount in order to prevent their overuse or excessive release into the surroundings. Worldwide food grain output soared during the green revolution, but at the expense of unbalanced application of synthetic fertilizers and chemical pesticides, seriously damaging our biosphere. In order to avoid making the same blunders again, future research must also look into any potential ecological risks related to these NFs.Furthermore, research must be done on bio-synthesized, green-manufactured, or nano-biofertilizers for better crop production in sustainable agricultural activities (Seleiman et al., 2020). Before the commercial sale or promotion of NFs, careful and empirical application of these products should be thoroughly reviewed. Prior to using different nanoparticles or nanofertilizers in agricultural productivity, future studies must concentrate on their safety, toxicity, and bioavailability. Table 1 outlines types, applications, effects, and risks associated with some of the nanofertilizers most frequently used in agricultural practices.

V. FUTURE RESEARCH AGENDA

According to environmentally friendly agriculture, nanotechnology can provide new and creative NFs, ensuring agricultural safety while considering sustainability concerns. The greater "surface-to-volume" ratio and regulated nutritional delivery of nanofertilizers provide them an edge over traditional fertilizers. Nanofertilizers, for example, may significantly enhance crop qualities and yields while releasing nutrients as much as 12 times more slowly than synthetic fertilizers. Through more efficient delivery of active ingredients, NFs can also assist in lowering fertilizer dosages, increasing nutrient absorption and NUE figures, and decreasing

fertilizer loss through volatilization, runoff, use of energy during the cultivation process, and leaching. For instance, whereas traditional fertilizers might release nutrients over 40–50 days, nanofertilizers require 4–10 days to do so. Accordingly, leaching and volatilization may cause synthetic fertilizers, particularly N-urea, to quickly lose over 50% of their nutrients after being applied in the field. Seed coverings and nano-sensors containing NFs may also lower environmental issues and crop production expenses. The benefits of nanofertilizers have opened up new avenues for sustainable and productive agriculture; nevertheless, various plant varieties behave differently following exposure to various nanomaterials, and precise data regarding the combined characteristics, i.e., permissible limits, and eco-toxicity of multiple nanomaterials remains ambiguous. In light of this, a practical foundation for NFs in the future innovative agriculture, a great deal of investigation into better synthesis methods, and a range of restoration and habitation databases may be necessary for an ecologically sound agricultural system.

VI. CONCLUSION

Nanofertilizers as a technology are the best innovation in this century, since theyincrease nutrient use efficiency and minimize environmental damage. Since they can release their nutrients gradually, they provide a sound option to the conventional fertilizers that lead to loss of nutrients via leaching and volatilization. However, there are some concerns about their long-term impact on the environment, i.e., their toxicity, as well as bioaccumulation. The future work should be aimed at the optimization of processes for NF synthesis, enhancing their eco-performance, and performing life-cycle assessments. It is also expected that combining both bio-based and green nanotechnology strategies would extend their applicability. Hence, when these challenges are addressed, nanofertilizers have potential in ensuring food safety and also improving environmental sustainability.

Conflict of Interest

The authors declare that they have no conflict of interest.

Authors' Contribution

Adnan Saleem: Conceptualization, writing – original draft, literature review. Ishrat Batool: Supervision, editing, and review of the manuscript.

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