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Enhancing Crop Production: Unveiling the Role of Nanofertilizers in Sustainable Agriculture and Precision Nutrient Management

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IMPROVING agricultural output worldwide to satisfy the demands of a rapidly expanding population may be possible, in part, through the creation and use of novel fertilizers made possible by cutting-edge nanotechnology. As a matter of fact, according to the literature assessment, there are designed nanomaterials that, at specific concentrations, can improve plant development. These materials could be utilized as nanofertilizers in agriculture to boost crop yields and reduce pollution. Nanofertilizers that enhance plant development, nanofertilizers that include nutrients, and nanofertilizers that contain micronutrients are the four main types of nanomaterials discussed in this article. Concerning the chemical makeup of the nanomaterials, the size of the particles, the concentrations used, the plant species that benefited, the techniques of plant incubation, and the features and rates of plant growth promotion, each category is addressed separately. Furthermore, we take a close look at each type of nanofertilizer to determine its relevance, potential future paths, and special research needs in the pursuit of sustainable agriculture. Lastly, this paper argues that protecting the environment and increasing food production should be top research priorities, and they propose developing macronutrient nanofertilizers containing N and P.

Keywords: Nanofertilizers, nanomaterials, sustainable agriculture, nutrient management.

1. Introduction

Projections indicate that by the year 2050, the global population will reach a staggering figure of over 9 billion individuals, signifying a substantial increase in the number of people inhabiting the planet (Singh et al., 2023). The increasing demand for food is outstripping the capacity of current farming systems, which rely heavily on fertilizers and climate change also aids as factor that impacted the agriculture production via decreasing the nutrient availability to plants by reduction in the uptake of fertilizers (Fig 1). Conventional fertilizers have low

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nutritional uptake efficiency (NUE), which measures how quickly plants absorb nutrients, store them in their tissues, and then release them to other parts of the plant (Fig 1). In reference to the nitrogen, phosphorus, and potassium NUEs, it is noteworthy that the current estimates for these elements are approximately 30–35%, 18–20%, and 35–40%, respectively.

This suggests that approximately 50% of the applied fertilizer is lost during the application process (Subramanian et al. 2015a; Elramady et al. 2021). To keep agricultural yields stable in the face of low NUEs, conventional fertilizer inputs must be increased. Sustainable agriculture is hindered, especially in developing nations, by the energy and materials needed for this approach, which puts a financial strain on farmers (Fig 1).

Additionally, excessive fertilizer use and runoff contribute to water body eutrophication and disturbance to the soil's structural components. They disrupt ecosystems' delicate nutrient and food chain balances, with far-reaching consequences (Tilman et al., 2002). Low NUEs may result from the conversion of nutrients and fertilizers into forms that plants are incapable of bio-absorbing or outpacing their release rates relative to plant absorption rates. Therefore, finding new and better NUE-boosting fertilizers is motivating. The unique properties of nanomaterials allow for innovation, fertilizer design and application (Dimkpa&Bindraban, 2018; Kah et al., 2018).

Bulk materials' physiochemical properties are different from those of NPs, which are minuscule molecules with a size range of 1 to 100 nm (Singh et al., 2023; Singh, Sengar, et al., 2024). The enhanced physical, chemical, and biological properties and functions of NPs may be attributed to their higher surface area to volume ratio, according to prior research (Rajput, Minkina, et al., 2021; Singh, Sharma, Rawat, Singh, et al., 2022; Verma et al., 2022b). Nano-fertilizers fertilizers are used to enhance plant growth and increase crop yield by delivering specific nutrients in nano sized form (Dimkpa et al., 2020; Kah et al., 2018). According to the nutrients that plants require, nano fertilizers can be categorized as either macro, micro, or nano-particulate (Chhipa and Joshi, 2016; Rajput, Singh, et al., 2021). Josef and Katarína (2015) stated that nano-fertilizers, characterized by a diameter below 100 nm, may be administered in liquid or powder form. They improve plant productivity by enhancing nutrient uptake and making nutrients more accessible to plants. According to (Subramanian et al. 2015b; Elramady et al. 2021), nanofertilizers possess a number of significant attributes, which comprise the following: (1) their capacity to promote plant growth via foliar and soil applications by delivering the suitable nutrients; (2) their cost-effectiveness and environmental friendliness as a source of plant nutrients; (3) their exceptional efficiency in fertilization; and (4) play pivotal function in mitigating pollution. Beyond their potential as an alternative to conventional fertilizers, nano-fertilizers also contribute to the remediation of contaminated water sources.

Researchers, policymakers, and businesses combined are very interested in the possibility of using nanostructured materials to improve NUE and controlled-release fertilizers, a huge credit to the proliferation of nanotechnology (Wang et al., 2016). In light of the importance of this field of research, the objective of this article is to provide an overview of the current nano-based techniques utilized to regulate the nutrient release from fertilizers in order to maximize their beneficial agronomic effects. On the basis of six distinct types of nanostructured materials, we examined and assessed the environmental implications, production, characteristics, and agricultural efficacy of slow-release fertilizers. Further evaluation was conducted to determine whether it is feasible to integrate nano-enabled controlled release technologies, which are presently employed in food, pesticide, and medication delivery systems, into the realm of fertilizer research and development. Considering the growing demand for novel fertilizers and the numerous benefits of nanotechnology, the overarching objective of this review is to facilitate the expansion of profitable and sustainable agriculture.

2. Need of nanofertilizers for Sustainable Agriculture: A Comparative analysis?

Chemical fertilizers are difficult for plants to absorb. Most chemical fertilizers' macronutrients are poorly soluble in soil, resulting in minimal intake. Thus, chemical fertilizers must be applied repeatedly. Increasing food demand encourages farmers to use more chemical fertilizers, harming soil and the environment. Overuse of chemical fertilizers damages soil structure and mineral cycles permanently. Overfertilization damages soil microorganisms, plants, and food chains across ecosystems, causing hereditary mutations. Agricultural nitrogen (N) and phosphorus (P) fertilizers are the main cause of global eutrophication (Kumar et al., 2020). A farmer's profit margin decreases with chemical fertilizers. Regular use of conventional fertilizers has caused groundwater contamination, water eutrophication, chemical burning, soil deterioration, and air pollution globally (Savci, 2012a). Conventional fertilizers reduce crop nutrient utilization efficiency (NUE) by releasing nutrients quickly or converting non-bioavailable nutrients (Sarmast et al., 2018).

Fertilizers, whether made of organic or synthetic materials, contain chemical components that boost plant growth and yield while also improving soil fertility and making up for micronutrient deficits. Encapsulating nanofertilizers improves nutrient absorption, which in turn decreases nutrient loss, promotes healthy plant development, and enhances crop quality (Chhipa, 2017a; Verma et al., 2022a). Because some plant-essential components are not readily available in soil, traditional fertilizers can only go so far. This can be caused by ineffective delivery to the target or by underutilization of the crop at the intended destination (Rameshaiah & Shabnam, 2015). The use of nanofertilizers has been proposed as a possible remedy (Adisa et al., 2019a). These fertilizers increase yields by enhancing plant performance, micronutrient uptake, and availability. Due to their large surface area, absorption capacity, and controlled-release dynamics to certain locations, nanofertilizers are considered intelligent delivery devices. It is possible to distinguish three distinct varieties of nanofertilizers by experimenting with various formulations: (a) Nanoscale fertilizer, which is a conventional fertilizer but is so small that it often takes the shape of nanoparticles. (b) Fertiliser that is applied to nanoparticles as a coating and (c) fertilizer that is intercalated into the nanoscale pores of a host material are both examples of nanoscale fertilizers (Adisa et al., 2019b; Parveen et al., 2016).

3. Macronutrient nanofertilizers

Nanofertilizers with high macronutrient content can effectively supply plants with the necessary nutrients, as they are composed of these chemical constituents. Proficient application of macronutrient fertilizers, predominantly nitrogen and phosphorus fertilizers, enhances the production of essential commodities such as food and fibre. Global macronutrient fertilizer (N+P+K) consumption peaked at 175.7 Mt in 2011 and is projected to decrease to 263 Mt by 2050 (Alexandratos& Bruinsma - FAO, 2012). Nitrogen-rich fertilizers have been instrumental in boosting global food production; over the past half-century, their use has increased food output per capita by approximately 40 percent (Smil, 2002). Moreover, a considerable amount of these essential nutrients (N and P) is discharged into ground and surface waters, thereby causing disruptions to aquatic ecosystems and presenting a risk to both human and aquatic life.

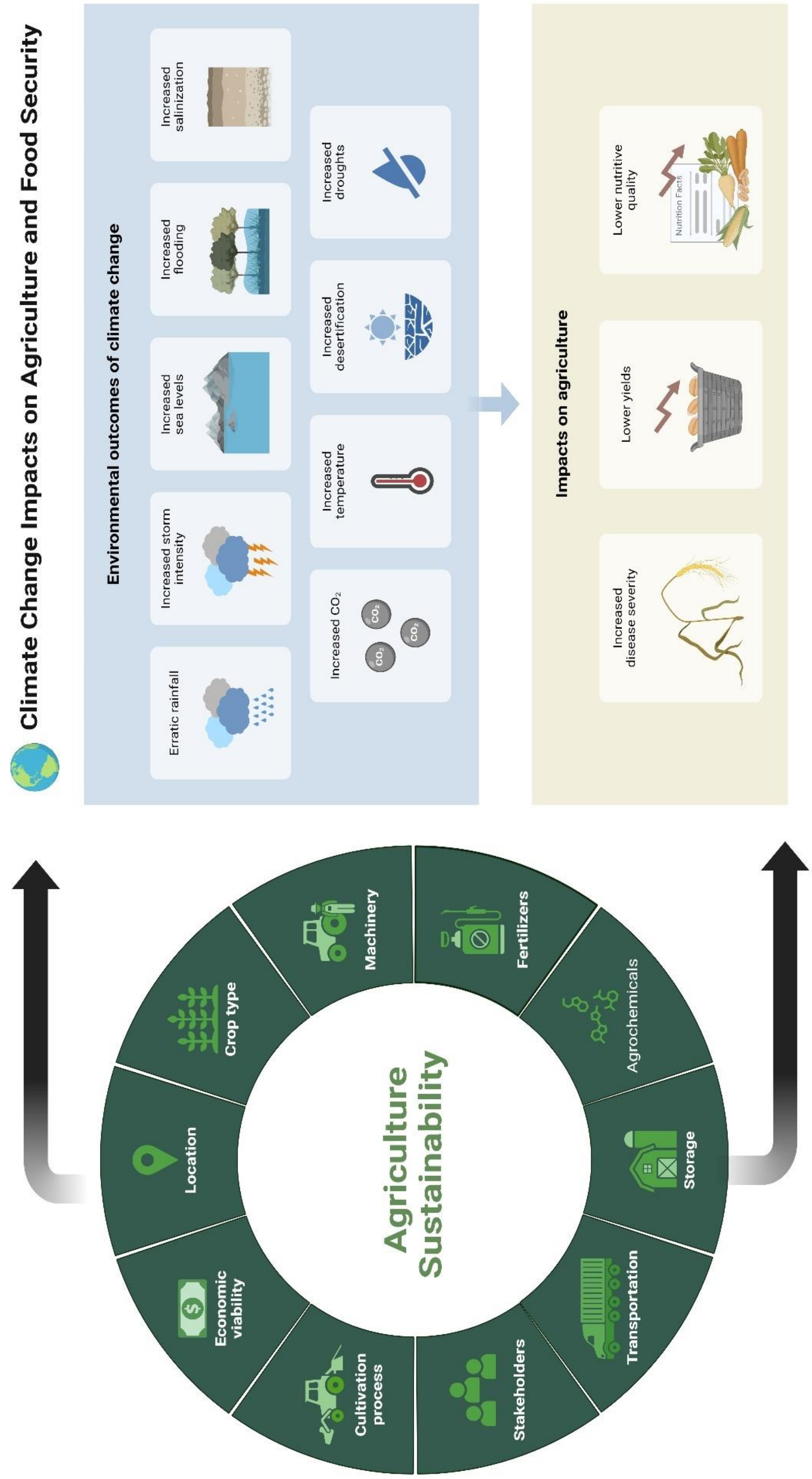

Fig. 1. Sustainable agriculture and impact of climate change on agriculture production and quality.

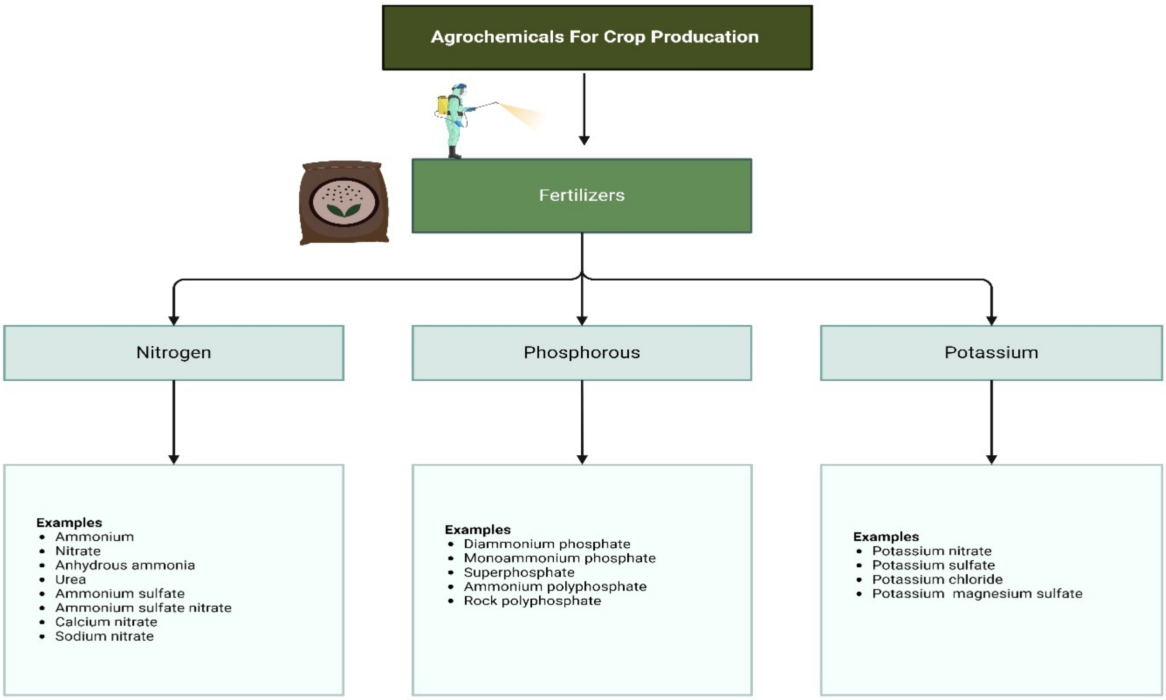

Fig. 2. Application and example of conventional fertilizers (CFs).

This is because these macronutrient fertilizers have a low efficiency (around 30–50%) and are applied heavily. As a result, the development of environmentally friendly and highly efficient macronutrient (N and P) nanofertilizers to replace conventional N and P fertilizers is a critical and urgent field of research that must be given top priority if we are to ensure environmentally sustainable food production. Nanofertilizers containing macronutrients are thus an area of intense focus in the fertilizer industry. Table 1 and the following provide a synopsis of a few potential macronutrient nanofertilizers (Fig 3).

3.1 Nitrogen NFs

Globally, nitrogen is the most critical nutrient in imposing constraints on agricultural productivity. Despite numerous endeavours, farmers continue to obtain an estimated 50% of their nitrogen requirements from plants (Carrascosa et al., 2023). A worldwide financial and ecological concern, nitrogen over-utilization has been done in the last several decades to attain desired agricultural yields (Savci, 2012b). Eutrophication and higher emissions of greenhouse gases are consequences of the current nitrogen fertilizers' low utilization efficiency of 20% (Kahrl et al., 2010). The majority of the nitrogen content in urea is lost as a result of its rapid volatilization and subsequent leaching following application. Nitrogen nanofertilizers involve the combination of nitrogen molecules with nanoparticles (NPs), including graphene, metal oxides, and carbon nanotubes. With more nitrogen available in the soil, plants can take in more nutrients thanks to this particle mix (Fig.:3). By gradually releasing nitrogen into the soil, these fertilizers effectively mitigate the risk of environmental damage resulting from runoff and leaching, as well as reduce the quantity of nitrogen in aquatic systems. While conventional fertilizers only release their nutrients for 300–350 hours, nanofertilizers can release them for up to 1200 hours, according to one study that tracked the release pattern of nitrogen-containing nanofertilizer formulations (Manikandan et al., 2016). Increasing N usage efficiency using zeolite nanofertilizer is suggested in another study (Carmona et al., 2021). Supplementary nutrition is facilitated by nitrogen-containing fertilizers, which influence plant’s plant's overall development and growth (Erisman et al., 2008). These nanofertilizers (urea) that are readily available in the market tend to dissipate after approximately 75% application as a result of rapid volatilization and leaching. Therefore, the disadvantages of nitrogen fertilizers involve inefficient utilization and the release of nitrogen into the environment, resulting in eutrophication and the emission of significant amounts of greenhouse gases (Kahrl et al., 2010). A cutting-edge nitrogen nanofertilizer has been developed by employing urea-coated hydroxyapatite NPs, which are rod-shaped entities characterized by an average aspect ratio of 10. This innovation enables precise application and a controlled discharge over time (Kottegoda et al., 2017). The chemical compatibility of these compound nanoparticles, as well as the abundance of nitrogen and phosphorus, were significant factors in their selection.

3.2 Phosphorous NFs

A crucial component for the development and growth of plants is phosphorus. A vital component of photosynthesis, it facilitates the assimilation of additional nutrients, such as nitrogen and potassium. A new kind of fertilizer called phosphorus nanofertilizers might completely alter the agricultural industry. They outperform traditional fertilizers in terms of efficiency, cost-effectiveness, and eco-friendliness.

Using a slow-release phosphorus nanofertilizer is one technique to retain phosphorus in the soil during a crop's development (Saraiva et al., 2022). A less expensive alternative to superphosphates, nano-rock phosphate was found to have comparable phosphorus utilization in an experiment with maize plants (Tang & Fei, 2021). The use of hydroxyapatite nano-formulations (nHAP; $Ca_{10}(PO_4)_6(OH)_2$) for phosphorus delivery to plants has recently been utilized (Yasmeen et al., 2022). The use of ultrasonic dispersion to apply natural raw phosphorite to seeds yielded encouraging results for the P nanofertilizer (Sharonova et al., 2015). Despite the fact that the soil typically contains an adequate quantity of phosphorus, producers are still required to apply P fertilizers because plants cannot depend on the soil levels. In order to enhance the effectiveness of converting native phosphorus to phosphorus that plants can readily absorb, zinc nanoparticles were employed. Zinc is an essential cofactor for many enzymes, including phosphatase and phytase. Plant development, yield, biomass, and nutritional value were all enhanced when ZnO NPs were added to cereals and legumes, which led to an 11% increase in P absorption and enzyme activities **(Fig 2)** (Raliya & Tarafdar, 2013). Cotton plants have also been found to be exposed to P-supplements and ZnO NPs (Vallee & Falchuk, 1993). The quantity of biomass, proteins, and photosynthetic pigments—which shield cotton from oxidative damage—increased when ZnO was combined with P (Vallee & Falchuk, 1993). Either producing P-based NPs or micronutrient-based NPs (such as Fe and Zn) can enhance P absorption by stimulating native P mobilization. In addition to promoting plant growth, this will also help address other issues, such as the environmental impacts of excessive phosphorus levels and the limited availability of phosphorus.

3.3 Potassium NFs

Nano potassium, also known as potassium nanofertilizers, is a modern innovation in agricultural technology. The small particles that make up these fertilizers allow them to reach the roots of plants by penetrating deeper into the soil. As a result, their heightened absorption rate enables them to supply plants with essential nutrients at a quicker and more efficient rate than conventional fertilizers. Furthermore, the greater solubility and leaching resistance of nano-potassium render it less susceptible to erosion by precipitation or irrigation (Ha et al., 2019). The aforementioned attributes significantly enhance the capacity of potassium-based nanofertilizers to sustain higher yields over extended durations.

4. Micronutrient nanofertilizers

4.1 Zinc NFs

Zinc is an essential element for multiple enzymes in plants that enhance the rate of metabolic processes. Insufficient zinc levels significantly impair the synthesis of chlorophyll, carbohydrates, and proteins in plants, leading to a complete cessation of plant growth and development. Zinc oxide nanofertilizers applied to soil enhance agricultural yields by augmenting the accessibility of zinc to plants. An additional advantage of zinc oxide nanofertilizers is their capacity to mitigate zinc leaching from soil, thereby reducing the probability of environmental pollution (Singh, Rajput, et al., 2024). Moreover, empirical evidence indicates that zinc oxide nanofertilizers might enhance the resistance of plants to biotic and abiotic stresses (Ahmed et al., 2022; Lindsay, 2018; R. Liu et al., 2016). According to reports, zinc oxide nanoparticles can enhance the growth and harvest of a variety of crops (J. Liu et al., 2023; Mukherjee et al., 2014; Singh et al., 2023; Singh, Sengar, et al., 2024; Singh, Sengar, Rajput, et al., 2022; Singh, Sengar, Shahi, et al., 2022; Singh, Singh Sengar, Singh, Shahi, et al., 2022; Skiba et al., 2020; Vankova et al., 2017). Recently, 20 mg L^{-1} ZnO NPs significantly improved the biochemical composition and numerous growth indices of *Citrus aurantium* fruit (Rajput et al., 2018).

A greenhouse study which found that the growth and development of cucumbers (*Cucumis sativus*) were enhanced by the addition of 400 and 800 mg kg^{-1} of ZnO-NPs to a soil mixture (L. Zhao et al., 2017). While the fruit dry weight exhibited a marginal increase of merely 0.6% in comparison to the control group, the data revealed that the dry mass of the plant roots was 1.1 and 1.6 times greater. The application of ZnO-NPs to cucumber fruits resulted in an increase in their starch content by 1.1-1.6 times, glutelin content by 0.9-2 times, and Zn content by 1.7-2.5 times. Furthermore, it was observed that ZnO-NPs did not have any negative impact on growth-related measurements (L. Zhao et al., 2013).

In their 2007 study, Lin and Xing found that compared to the control group, which received only deionized or DI water, germinated radish and rape seeds treated with a concentration of 2 mg L^{-1} of ZnO-NPs showed improved root elongation (Lin and Xing, 2007). Similarly, enhanced growth was observed in ryegrass seedlings treated with 2 mg L^{-1} of metallic Zn-NPs. The seedlings underwent inhibition or death when exposed to Zn-NPs in quantities exceeding the acceptable limits. The majority of studies on the impact of Zn-NPs on organisms have concluded that Zn-NPs pose a significant risk to plants and crops, with only a few exceptions. Various investigations assessed the intense harmful effects of ZnO-NPs at extremely elevated concentrations, ranging from 400 to 2000 mg L^{-1} (C. W. Lee et al., 2010; Lin and Xing, 2007; López-Moreno et al., 2010; Priester et al., 2012). As per the findings of (Lin and Xing 2008), the introduction of zinc nanoparticles at a concentration of 10 mg L^{-1} does not have a beneficial impact on the growth of ryegrass. Phytotoxicity may result from the application of higher concentrations of zinc, given that optimal growth for most plants requires no more than 0.05 mg L^{-1} of zinc in soil solution.

4.2 Iron NFs

Many soils have insufficient amounts of iron, a micronutrient that is crucial for plant growth, because of its poor solubility. The goal of developing iron nanofertilizers was to make iron more bioavailable to plants. Nanocomposites, nanoencapsulation iron, and nanosized iron particles are some of the many shapes that iron nanofertilizers can take (Liu et al. 2018; Sharipova et al. 2020). Iron oxide or sulphide, which are nanosized iron particles, are the most basic iron nano-fertilisers. The enhanced absorption capacity of plants relative to conventional iron fertilizers is attributed to the diminutive size of these particles, which facilitates their penetration through the soil surface. Iron particles that have been nano-encapsulated are lipid or biopolymer-coated for protection. These coatings aid in the retention of iron particles in the soil for an extended period of time by inhibiting their oxidation. Iron nanoparticles are mixed with zeolites, clay, or humic acid to form nanocomposites. The purpose of these nanocomposites is to enhance iron absorption in plants by creating an adsorptive or catalytic surface. Nanofertilizers made of iron can boost agricultural production, fix soils that are low in iron, and make water better for aquatic life (Pitambara et al. 2019). Additionally, iron nanofertilizers can mitigate acid rain's negative impacts and restore polluted soils (Cui et al., 2017). In a greenhouse test utilizing hydroponic conditions, (Ghafariyan et al. 2013) discovered that the concentration of sub-apical leaf chlorophyll in soybeans increased significantly when subjected to low concentrations of super-paramagnetic Fe-NPs. These results indicate that soybeans might be capable of utilizing these NPs as a Fe source, thereby mitigating the chlorotic symptoms associated with Fe deficiency. At concentrations < 45 mg L^{-1}, use of Fe-NPs had an effect comparable to that of Fe-EDTA, an efficient source of iron for plants. According to (Delfani et al. 2014) black-eyed peas were shown to have considerably higher levels of chlorophyll content (by 10%), iron content (by 34%), weight of 1000 seeds (by 7%), and number of pods per plant (by 47%) when 500 mg L^{-1} Fe-NPs were applied foliarly. The control group did not show any significant changes. Applying Fe-NPs also had a greater impact on crop performance compared to using a standard iron salt. The metrics increased by 28%, 4%, 45%, and 12%, respectively, when comparing the outcomes of treatment with Fe-NPs to those of treatment with Fe salt. The addition of Mg-NPs to Fe-NPs significantly enhanced the beneficial effects observed in black-eyed peas. Hoagland and Arnon (1950) state that the optimal iron concentration for plant growth in soil solutions is 1 to 5 mg/L.

4.3 Manganese NFs

Enzymes are cofactors of manganese (Mn), which provides them with resistance to a vast array of environmental stresses. In addition, secondary metabolites including lignin and flavonoids, as well as ATP, chlorophyll, proteins, fatty acids, and chlorophyll, all require manganese (Palmqvist et al., 2017). In contrast to the commercially available $MnSO_4$ salt, metallic Mn-NPs offer a greater quantity of Mn as a micronutrient (Pradhan et al., 2013). Pradhan et al. (2013) discovered that the introduction of manganese nanoparticles resulted in enhanced photosynthesis and growth of mung bean (*Vigna radiata*). A period of 15 days was devoted to the cultivation of mung bean seedlings in growing chambers containing an inert medium (perlite) and Hoagland solution. The largest growth boost in contrast to the group of controls (without Mn) was observed in root length (52% increase), shoot length (38% increase), number of rootlets (71% increase), fresh biomass (38% increase), and dry biomass (100% increase) when Mn-NPs were applied at 0.05 mg L^{-1} concentration. The application of Mn-NP resulted in 2%, 10%, 28%, 8%, and 100% improvements in these parameters compared to seedlings treated with $MnSO_4$ salt, respectively. Surprisingly, the application of $MnSO_4$ at a concentration of 1 mg L^{-1} resulted in the inhibition of plant development. However, the reaction remained positive when Mn-NPs were utilized. For plants to grow healthily, the soil solution typically needs 0.5 mg L^{-1} of Mn.

4.4 Boron NFs

The soil generally lacks the element boron, which is essential for plants to grow optimally. To make up for this shortfall, boron-based nanofertilizers supply boron to crops in a more concentrated and targeted form. Borate-based nanofertilizers are produced through the combination of borate with various compounds, including humic acid. As a foliar spray, they may be applied to crops or soils after becoming suspended in a liquid or solid state. Nanofertilizers based on boron can deliver micronutrients to plants by penetrating their cells (Deshmukh et al., 2022). Both zinc and boron nanofertilizers used in lower concentrations and applied as foliar spray were shown to enhance pomegranate fruit quality and yield in a recent study. When applied before full bloom, nano-Zn chelate and nano-B chelate fertilizers were found to increase leaf concentrations of both microelements (Davarpanah et al., 2016).

4.5 Copper NFs

Copper nanofertilizers are very efficient nutrient delivery systems for plants. The microscopic copper ions can enter plant cells and supply the roots with vital nutrients (Vardumyan et al., 2024). Nutrient absorption is accelerated and enhanced by direct administration. Nanofertilizers made of copper pose no health risks whatsoever. Their safety for both people and animals has been confirmed by extensive testing. Their resistance to runoff and leaching makes them a great option for environmentally conscious farming. It has been indicated that with the application of copper nanofertilizers crop yields in crops like maize and wheat can be improved (Jyothi and Hebsur, 2017). The natural antibacterial and antifungal properties of copper make them useful in enhancing plant resistance to pests and illnesses (Chhipa, 2017b; Deshmukh et al., 2022). However, copper nanofertilizers are far more affordable and easier to apply than conventional fertilizers. For small-scale farmers without the capital to invest in more expensive alternatives, these solutions' affordability is a major selling point. A study that was conducted by (Nekrasova et al. 2011) affirm that low concentrations Cu-NPs i.e., lesser than 0.25 mg L^{-1} as Cu enhanced the rate of photosynthesis by 35% compared to the group of plants that were not exposed to Cu. This enhancement occurred following a three-day incubation period with a particular variety of waterweed (*Elodea densa* Planch.).

After a period of 15 days, the growth of lettuce seedlings was considerably increased by 40% and 91% with the addition of 130 and 600 mg kg^{-1} of metallic Cu-NPs to soil, respectively (Shah & Belozerova, 2009). Some research suggested that seedling growth of mung bean, wheat, and yellow squash was adversely affected by metallic Cu-NPs at concentrations ranging from 200 to 1000 mg L^{-1} (W. M. Lee et al., 2008; Musante & White, 2012). Based on the findings by (Stampoulis et al. 2009), it was observed that the biomass of courgette (*Cucurbita pepo* cv. costataromanesco) decreased by 90% after 14 days of incubation in Hoagland solution when exposed to 1000 mg L^{-1} of metallic Cu-NPs, in comparison to the control group (without Cu). Phytotoxicity may occur at elevated levels of Cu, while the optimal concentration of Cu in water for promoting plant growth is only 0.02 mg L^{-1}.

5. Application and Transportation of NFs

5.1 Foliar Spraying

Foliar spraying is a cutting-edge technique that allows plants to quickly absorb nutrients through their leaves by applying liquid fertilizers straight to the foliage. This technology enables precise and efficient delivery of nanofertilizer to the plant's leaf surface, resulting in targeted, optimal, fast, and accurate transfer. NPs have a lot of potential as a vehicle for delivering fertilizers, pesticides, herbicides, and essential nutrients to plants when applied topically.

This method improves the efficacy of these drugs by using delayed release mechanisms. While the mechanism of action is heavily influenced by the particle size, nanoparticles (NPs) applied via foliar means may be absorbed via endocytosis, stomata, or direct absorption.

There are obstacles that can prevent these particles from being taken in, such as cell walls and leaf wax. Most NPs, after ingested, end up in vacuoles. Absorption and transport of NPs are affected by several parameters, such as ambient conditions, NP physical qualities, and plant traits. Improved fertilizer absorption, faster response, and lower leaching and run-off are just a few of the benefits of foliar spraying over more conventional soil applications. Numerous studies have demonstrated that foliar application of nanofertilizers significantly improves nutrient uptake, stimulates plant growth, and increases crop yield. A 36.6% increase in wheat yield and a 28.0% increase in bitter melon yield were achieved by foliar applications of CeO_2- and carbon-based-NPs. Another study found that when tomato plants were treated with copper NPs through foliar application, fruit yield was improved by 80% but the concentration of copper needed was 30% less than with traditional copper-based fungicides (Essa et al., 2021).

5.2 Soil Application

Soil broadcasting is a typical technique for applying fertilizer. Nanofertilizers are easily absorbed by plants when applied directly to the rootzone, particularly in the area close to the root tip. Nanofertilizer uptake mechanisms are complicated by soil's complex and dynamic physicochemical properties, including pH, CEC, various nutrients, root exudates, organic matter, and its biotic population, which consists of microorganisms (Chugh et al., 2021). Soil or rhizospheric microbial communities can be affected by the localized application of high concentrations of NPs (Raliya et al., 2018). In addition, the particle can clump together due to the soil's physicochemical characteristics.

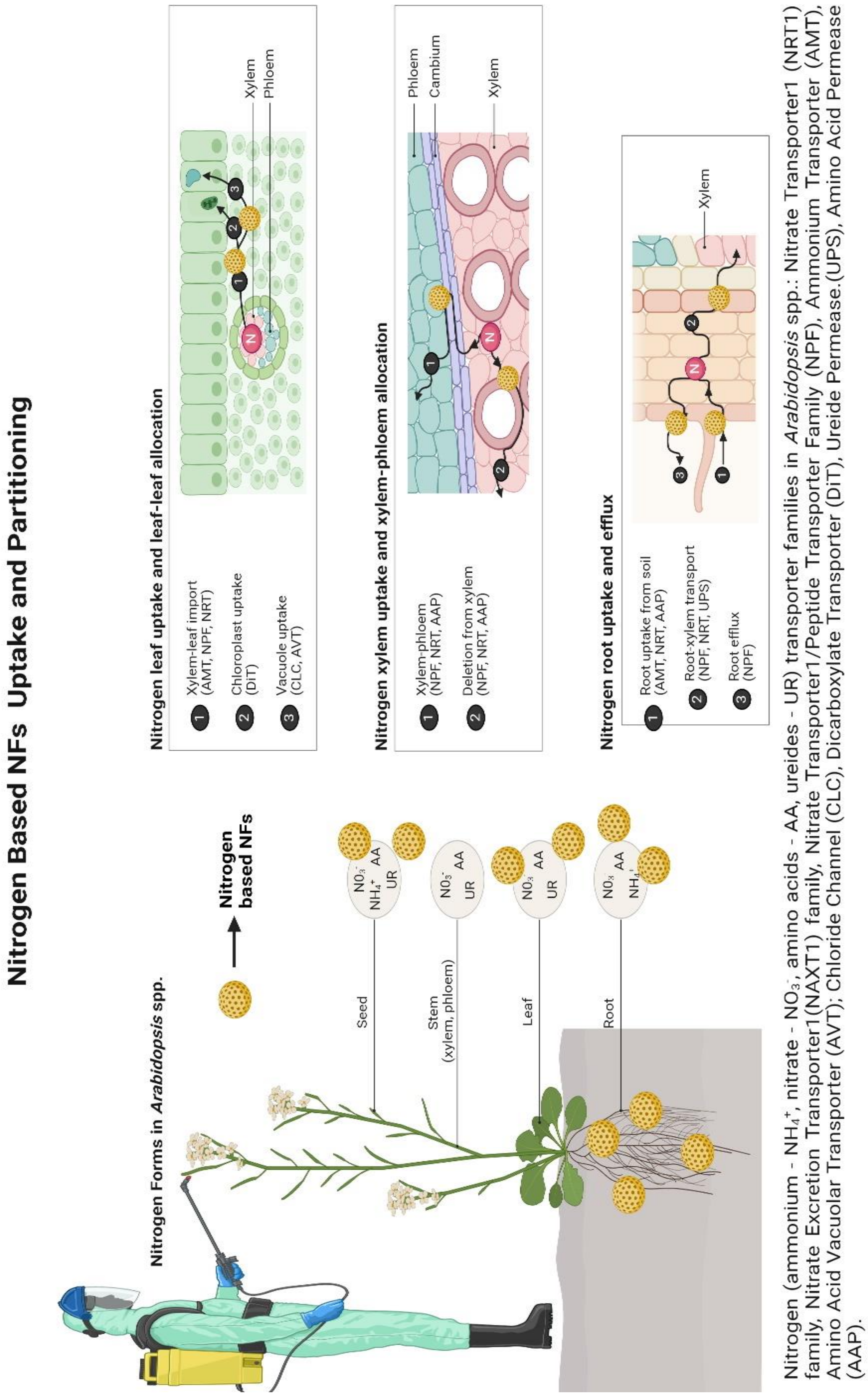

Fig. 3. Transport and Absorption of Nitrogen based NFs through diverse pathways and their translocation throughout the plant system

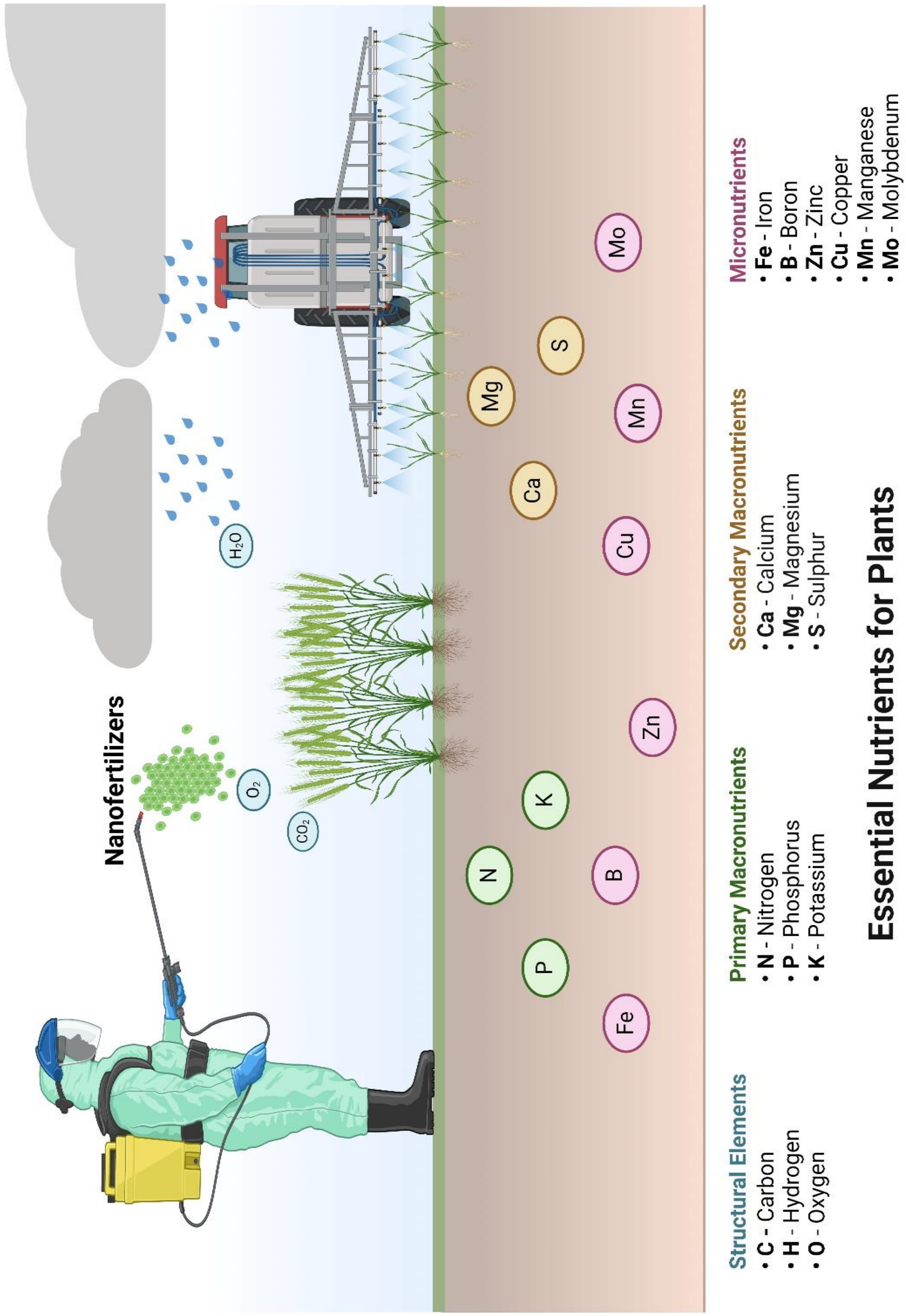

Fig. 4. Application of different type NFs which aid for better growth and development of plant.

Foliar spray significantly outperformed soil application in terms of nutrient uptake, according to comparison research (Raliya et al., 2018). NFs can easily penetrate the root zone through the lateral root connections of the rhizo-dermis, particularly at the root tip, while the upper sections of the root are impermeable because to suberin. For that reason, applying nanofertilizers to the leaves is better than doing so in the soil (Chichiriccò and Poma, 2015; Senchukova, 2019).

5.3 Seed Priming

To maximize plant development and growth by modulating metabolic and signalling cascades, priming seeds is a crucial procedure performed prior to planting.

Recent studies have proven that soaking seeds in nanofertilizers can significantly reduce fertilizer use without compromising quality (Mahakham et al., 2017; Rai-Kalal & Jajoo, 2021; D. Sharma et al., 2021).

Nano-biofertilizers diffuse inside seeds and penetrate their pores, stimulating growth hormone activation, and enhancing germination and development. Additionally, it has been demonstrated that priming seeds with nanofertilizers increases germination rates by reducing reactive oxygen species and regulating plant growth hormones (Mahakham et al., 2017; D. Sharma et al., 2021). Additionally, priming seeds enhances resistance during germination by controlling the expression of numerous genes related to plant resilience (Bayat et al., 2020). Although traditional methods of priming seeds include dissolving the seed coat using water, nutrients, or hormones, the latest technique of nano-priming seeds, which involves coating seeds with nanofertilizers, is highly effective in preventing a large portion of seeds from being infected.

6. NFs for Sustainable Agriculture

6.1 NFs for Plant Growth and Development

Nanofertilizers expand nutrient availability, thereby significantly facilitating the physiological and biochemical processes of crops. The expedited gas exchange through which the nano NPK formulation traversed the stomata of the wheat leaves resulted in an increase in leaf growth upon application.

This was achieved through the enhancement of nutrient accessibility (Mohammad Abdel-Aziz et al., 2018). Both cotton (Rezaei and Abbasi, 2014) and pearl millet (Tarafdar et al., 2014) showed similar impacts. Spraying plants with a zinc nano-fertilizer increased their dry biomass and height significantly (Gharaei et al., 2015). Physiological processes including antioxidant activity and chlorophyll content may be improved if plant quantity and quality are increased (Rezaei & Abbasi, 2014). Zinc has the ability to affect a number of biochemical processes, such as those involved in the synthesis of natural auxin (IAA), protein and carbohydrate metabolism, pollen production, and cellular membrane integrity (Alloway, 2008). Unlike traditional urea fertilizer, which releases nitrogen every 30 days, these nanofertilizers release it slowly over the course of 60 days of plant growth (Kottegoda et al., 2011). A study demonstrated that the release curve of urea, when encased within mesoporous silica nanoparticles, exhibited a significant improvement, being five times more effective (Wanyika et al., 2012). Figure 4 shows how the slow-release nanofertilizer promotes crop productivity while preventing environmental loss. The use of nanoparticles like Al_2O_3, TiO_2, CeO_2, FeO, and ZnO has significantly improved agricultural productivity in various crops (Table 1). Both seed germination and seedling growth are significantly impacted using nanofertilizers (Fig. 4). Seeds treated with Au, CuO, and TiO_2 nanoparticles exhibited higher rates of seed germination (Dhir, 2021). Rice (*Oryza sativa*), groundnut (*Arachis hypogeal*) and spiny amaranth (*Amaranthus spinosus*) all had better germination rates after being fertilized with calcium phosphate nanogel (Dhir, 2021). Seed vigor and water permeability are both enhanced by nanofertilizer. According to (Prasad et al. 2012), after being exposed to nano-ZnO, peanut seeds exhibited higher rates of germination and root growth. Hydromelon (Acharya et al., 2020), mustard (Arora et al., 2012), corn (Choudhary et al., 2019; Van Nguyen et al., 2022), wheat (Razzaq et al., 2016), millet

(Sathiyabama & Manikandan, 2021), fenugreek (Sadak & Bakry, 2020) and many more crops also benefit from nanoparticle application, which increases plant growth and yield.

Table 1. Application of different NFs for crop growth and development.

Nano Fertilizer	Crops	Mode of application	Concentration	Effect	References
Macro Nutrients					
Nitrogen	Chilli (*Capsicum annuum*. L)	Foliar Spray	0.4%	Enhanced growth and yield	(Sunil et al., 2024)
	Grapes (*Vitis vinifera* L.)	Foliar Spray	10%	Increased total yield and carotenoid content	(Awad et al., 2024)
Phosphors	Snap bean (*Phaseolus vulgaris* L.)	Soil and Foliar Spray	20% soil application and 5% foliar spray of nano calcium phosphate	Increased yield and crude protein percentage	(Abd El-Ghany et al., 2021)
Potassium	Olive (*Olea europaea* L.)	Foliar Spray	3 g L^{-1}	Improved leaf mineral content and enhanced the oil content	(Rohi Vishekaii et al., 2023)
	Eggplant (*Solanum melongena* L.)	Foliar Spray	1.5 g L^{-1}	Enhanced plant height, leaf area and dry weight.	(Ali et al., 2024)
Micro Nutrients					
Zinc	Grape vine (*Vitis vinifera* L.)	Soil	500 mg/kg nano Zn chelate	Increased anthocyanin, titratable acid, peroxidase activity, protein, ascorbic acid, iron, and potassium	(Mahdavi et al., 2022)
	Cherry tomato (*Solanum lycopersicum*L.)	Soil	3 mg of Zinc per kg	Higher crop yield and adequate zinc fortification	(Almendros et al., 2022)
Iron	Orange (*Citrus sinensis*L. osbeck)	Foliar Spray	0.1 %	Increase in yield and TSS	(El-Gioushy et al., 2021)
	Cucumber (*Cucumis sativus* L.)	Foliar Spray	0, 50, 75 and 100 mg L^{-1}	Increase in yield and bioactive compounds	(Guillén-Enríquez et al., 2022)
Boron	Olive (*Olea europaea* L.)	Foliar Spray	20 mg L^{-1}	Maximum fruit set and high seed oil percentage	(Genaidy et al., 2020)
	Faba bean (*Vicia faba* L.)	Foliar Spray	10 mg L^{-1}	Increase in number of pods per plant and yield	(Al-Hasany et al.)
Mangnese	Tomato (*Solanum lycopersicum* L.)	Foliar Spray	10 mg L^{-1}	Increasedthe leaf chlorophyll content, flowering and production	(Yue et al., 2022)
	Radish (*Raphanus sativus* L.)	Soil	50 mg L^{-1}	enhanced root elongation and seed vigour	(W. Zhao et al., 2024)
Copper	Melon (*Cucumis melo* L.)	Foliar Spray	9 mg L^{-1}	Improved the physical and nutraceutical quality	(Fortis-Hernández et al., 2022)
	Pear (*Pyrus communis* L.)	Foliar Spray	20 %	Enhanced vegetative growth and fruit set	(Hafez et al. 2021)

6.2 Impact of NFs on yield and Production attributes

Several crops have had their yields increased or their yield-contributing features documented because of NF application. Nano micronutrients had a more noticeable impact on increasing yield than CFs (Janmohammadi et al., 2016). Previous research has shown that using NF instead of CFs , production of various crops increased viz., rice (Al-Khuzai and Al-Juthery, 2020), wheat(Mehta & Bharat, 2019), and pearl millet(Nandhini et al., 2019). Numerous studies have demonstrated that NFs, similar to their effects on cereals, positively influence the enhancement of pulse yield (Table 1). Upon the introduction of nano-sized Zn and Fe ions, both the height and quantity of primary branches of chickpea plants exhibited an increase (Podgorica Tului et al., 2021). (Sharma et al. 2022) found that nano MgO increased the length of the shoot-root, fresh biomass, and chlorophyll content in horse gram. It was discovered by researchers that the application of nano-Zn and Fe to chickpeas resulted in a higher seed yield in comparison to the control group (Drostkar et al., 2016). Seed yield was 26% higher in green gram crops treated with a mixture of silver and zinc nanoparticles (20 ppm + 6 ppm) compared to control crops (Wasaya, 2020). Researchers found that barley plants with increased pigment production and RUBISCO activity had better photosynthesis (Janmohammadi et al., 2016). Additionally, it has been observed that the use of nano Fe and Zn in chickpea can improve nitrogen metabolism, cell multiplication, photosynthesis, and auxin synthesis (Podgorica Tului et al., 2021). NFs additionally stimulate the activity of enzymes involved in metabolic pathways, such as the protein and carbohydrate metabolism, as well as the metabolism of growth regulators (Drostkar et al., 2016). According to (Khot et al. 2012), the use of TiO_2 nanoparticles accelerated germination by producing reactive anions, which aided in water accumulation and increased oxygen uptake rates. Plants with an excess of ZnO nanoparticles have longer, stronger roots that can draw more water and nutrients from the soil, while plants with a deficit of Zn have shorter, weaker roots (Wasaya et al., 2020).

7. Limitation of NFs

For NFs to be efficiently transported and applied to crop plants, their size is a crucial consideration. Enhancement of bioavailability, utilization, effective penetration, and release in plant systems can be accomplished by manipulating the fundamental characteristics of NFs, including their increased surface area and reduced particle size (Abdulrhman et al. 2021). Several methods, such as SEM (scanning electron microscopy), TEM (transmission electron microscopy), DLS (size distribution spectroscopy) and ultraviolet-visible spectroscopy, are used to ascertain the shape, dispersion, and dimensions of NFs grounded on NPs, such as zinc oxide NPs (5 nm), iron oxide NPs (22 nm), and so on (Murgueitio-Herrera et al., 2022a). NFs are more readily transported into and out of cells via ion channels and molecular transporters due to their diminutive size (Hasanuzzaman et al., 2020; Zulfiqar & Ashraf, 2021). This facilitates the activation of various metabolic networks and signalling cascades that are connected to plant hormones or other growth modulators. Hydroxyapatite ($Ca_5(PO_4)_3OH$) nanoparticles with a size of approximately 16 nm were found to have the ability to improve soybean growth metrics when tested in a greenhouse setting (R. Liu & Lal, 2014). In order to increase the physiological outcome in agricultural plants, the size of NFs is one of the main parameters evaluated during their manufacture. To illustrate, NFs with sizes between 4 and 100 nm have the potential to quickly pass through cuticle layers, causing a cascade of physiological impacts in plants once they breach the waxy layer barrier (Chen et al., 2010). Nano-hydroxyapatite (NHAP)—a small, loss-reducing, and fertilizer-loaded material—can achieve both the fertilizer's release and the crop's absorption (Elsayed et al., 2022). For instance, NPs below 100 nm are frequently employed as fertilizers to supplement nutrients effectively and are environmentally friendly for sustainable agricultural production systems, according to a study (Khan et al., 2022), Therefore, it has been discovered that this size range allows for various metabolic networks in plant systems, which in turn enhances photosynthetic efficiency. The greater surface area of smaller NFs enhances their absorption and enables them to more efficiently penetrate plant cells (Tabrez et al., 2022). To illustrate the point, NFs have a surface area to volume ratio that is ten times higher than that of conventional urea fertilizer liquid NPs, which range in size from twenty to fifty nanometers. Additionally, NFs can pass through stomatal holes in leaves more easily due to their tiny size, which increases the contact area on leaf surfaces (Rios et al., 2020; Francis et al., 2020). The NFs composed of ZnO NPs obtained from the leaves of *Azadirachta indica* exhibited a spherical morphology and a maximum size of 50 nm on average (Singh et al., 2018). In addition, NFs measuring 40 nm in size and having a circular shape significantly enhanced the seed germination of tomato and fenugreek (Shaik et al., 2020). The NFs exhibit a range of diameters, including 10.5 nm for MnO, 7.8 nm for FeO, and 9.5 nm for ZnO, which facilitate their connection with stomata and enable effortless transport to other regions of the plant (Murgueitio-Herrera et al., 2022a). Using 20 nm γ-Fe_2O_3 NPs as NFs was demonstrated to increase the biomass and root size of peanut plants (Ramyadevi et al., 2012). A prior investigation demonstrated that the implementation of 50 nm α-Fe_2O_3 NPs enhanced the photosynthetic efficiency of soybean (Alidoust and Isoda, 2013). Research has shown that fluorescently tagged NPs can efficiently accumulate by crossing the epidermal layers below the cuticle, as well as the waxy layers in leaves (Nadiminti et al., 2013). Small gold nanoparticles (AuNPs) cling to soil in the rhizosphere, suggesting that they might easily penetrate neighbouring soils and target crop plant roots (Ebbs et al., 2010). Frequently, gold nanoparticles (AuNPs) between 10 and 50 nm in diameter were introduced into the roots of wheat and tobacco (Judy et al., 2012). Similarly, it has been observed that NFs measuring 43 nm in diameter exhibit greater capability of penetrating the foliage via stomata in *Vicia faba*, as opposed to NFs measuring 1 μm in diameter (Cao et al., 2019). Translocation to all systemic sites of plants was observed in foliar sprays containing nanoparticles (NFs; ZnO MnO-NPs) smaller than 12 nm (Murgueitio-Herrera et al., 2022a). Furthermore, the findings demonstrated that NFs induced substantial advantageous responses in cabbage plants, as evidenced by the augmentation of root development, dry biomass, and chlorophyll levels. When evaluated in hydroponic and foliar applications, NFs derived from NPs such as copper oxide and zinc oxide (with a size less than 100 nm) improved the agronomic characteristics of *Amaranthus hybridus* (Francis et al., 2022).

9. Environmental Considerations and Toxicity-Related Concerns of NFs

Nanoparticles are incredibly useful in many important fields, including medicine, gardening, and more. However, the precise risks that these substances pose to human health and the environment remain unknown. In the pursuit of determining the hazardous nature of these substances and devising safe methods of their application, the term "nano-toxicology" becomes significant (Oberdörster et al., 2005). Size and form, chemical substrate, synthesis process, biological substrate, and interactions in the medium of applications are among the several aspects that can make it difficult to compare the protective or toxic character of these nanomaterials (Riediker et al., 2004). NPs toxicological characteristics should be time-and item-specific (Oberdörster et al., 2005). It is imperative to ascertain the quantities of NPs that might persist in the environment and/or come into contact with living organisms by analyzing the toxicological data of each nano-product.

Notwithstanding the absence of definitive evidence linking NPs to human illness, scholarly investigations have demonstrated their capacity to induce genotoxic effects, including DNA damage and inflammatory responses within cells, which could potentially lead to toxicological ramifications (Bahadar et al., 2016). On the contrary, the effects of nanoproducts on the promotion of plant crops are more conspicuous and encompass ecological sustainability, economic stability, and biological durability. Plants treated with nanomaterials are better able to withstand both biotic and abiotic stresseswhereas plants fertilized with nanoparticles are healthier overall (Tiwari et al., 2012). Thorough risk assessments must precede the implementation of nanotechnology. Prior to the sale of a new nanofertilizer, it is imperative to employ regulatory measures and product redesign that evaluate, validate, and mitigate the potential adverse effects on public health and the environment (Nel et al. 2006). The behaviour and toxicity of NPs are influenced by formulation materials, size, dosage, and other factors (Adisa et al., 2019). NPs have negative impacts on plants at larger concentrations but have positive benefits at lower levels when applied under certain conditions. Although modified nanofibers are phytotoxic when used at high quantities (>500 mg L^{-1}), Reddy et al. (2016) but helpful when applied at lower doses (50 mg L^{-1}) (Reddy et al., 2016). Plants exposed to high concentrations of ZnO NPs had their roots obstructed, which led to a decrease in the uptake of other supplements and a loss of macro- or micronutrients (Nair & Chung, 2017). When NPs made of chemicals react with other substances, they can release dangerous consequences (Nair & Chung, 2017). The present inclination towards bio-based nanoparticle synthesis represents an endeavour to address this concern. Atmospheric factors influence the security and behaviour of nanomaterials due to the fact that they are innocuous to soil microbes but detrimental to marine microflora (Lyon et al., 2005). Following careful consideration of the potential adverse effects of NPs products, the Food and Drug Administration (FDA) of the United States has concluded that they do not present any risk to human health (Bahadar et al., 2016).

8. Nano-Precision Nutrient Management

What does precision nutrient management (PNM) mean? What are the main factors controlling the PNM? Is there any relation between nanotechnology and PNM? To what extent can nanofertilizers fulfil this relation?

Precision nutrient management is defined as “"PNM is *a management strategy to optimize nutrient application ratio, rate, timing, place, and method better to match nutrient supply and crop nutrient demand in amount, space, and time for increased nutrient use efficiency, yield, crop quality, and economic returns and protection of the environment*”.". PNM can also call precision fertilization, variable rate nutrient management, or smart nutrient management (Miao 2023). PNM depends on many factors including soil and landscape conditions (i.e., the spatial variability of soil fertility and crop yield), along with management practices, genetic differences, weather conditions, and their dynamic interactions (Miao 2023). The main goal of PNM is to minimize nutrient loss, enhance crop productivity, and promote sustainable farming practices. There are many techniques for precision nutrient application already designed to optimize nutrient delivery such as geographic information systems (GIS), global positioning systems (GPS), variable rate technology, sensor-based techniques, drones and unmanned aerial vehicles, and real-time monitoring and data analysis (Pullanagari and Cavalli 2023). PNM can be achieved through many approaches like smart-fertilizers or nano-fertilizers (Abdalla et al., 2022). Fig.5 clearly depicts that precision farming or smart agriculture has a strong link with nanotechnology, which offers many potential solutions for sustainable agroecosystems, such as improvement in nutrient use efficiency and minimizing the adverse environmental effects of agricultural production (Duhan et al., 2017; Zain et al., 2024). Along with nano-sensors, the biosynthesis of nano-agrochemicals has recently gotten more concerns as it can be affordable and eco-friendly compared to traditional chemical synthesis (Sharma *et al.* 2023). More studies are expected to be needed in the future to highlight and focus on these biological nano-agrochemicals, including nanofertilizers and nanopesticides.

10. Future Directions

The use of nanoparticles in fertilizers has the potential to improve agricultural yields while decreasing the negative effects of traditional fertilizers on the environment(Parveen et al., 2016). Nanozeolites, nanochitosan, and metal oxide nanoparticles are just a few of the nanomaterials that scientists are investigating in depth for their possible ability to enhance soil nutrient absorption and retention(Bradu et al., 2023). The development of controlled-release nanofertilizers has made great strides; these fertilizers gradually release nutrients, minimizing the need for treatment frequency and the risk of nutrient loss.Critical areas of research and development must be prioritized in order to develop and use nano fertilizers in farming(Savarimuthu et al., 2021).

The agricultural industry holds significant promise for nanofertilizers due to their manifold advantages.

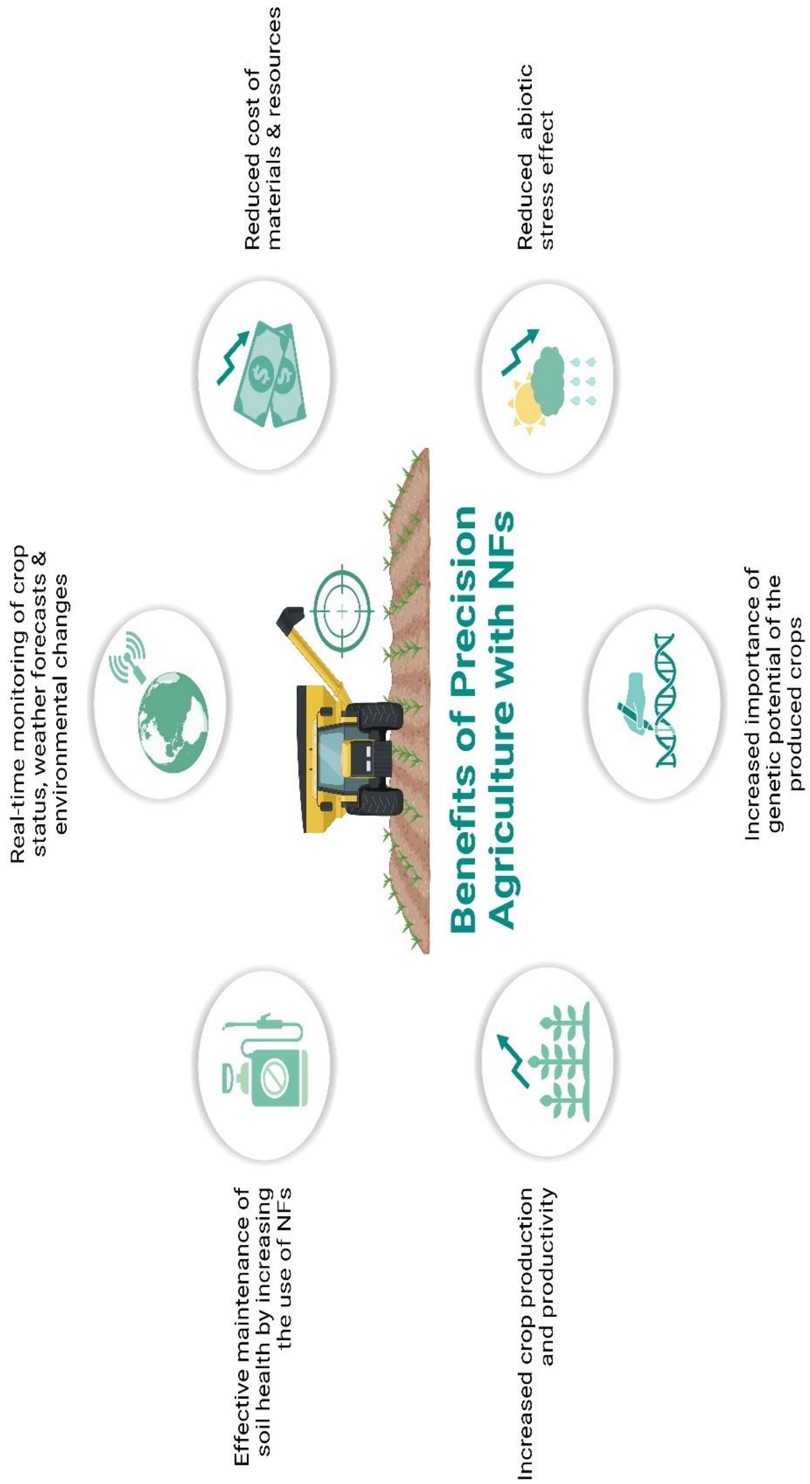

Fig. 5. The use of NFs in conjunction with Internet of Things (IoT) systems and various sensors for precision agriculture.

However, in order to optimize the physicochemical characteristics of nanomaterials and minimize dangers related to their usage, future research on nanofertilizers should concentrate on establishing cost-effective and environmentally friendly ways of synthesizing these materials. We require GTI and IoT technologies to build future goods that are biodegradable, long-lasting, and sustainable(Fig.:5). As a whole, GTI encompasses all advances that considerably enhance the use of natural resources while simultaneously decreasing negative effects on the environment(Lombi et al., 2019). The goal is to create formulations that can release nutrients precisely when and where they are needed. This will be achieved by utilizing "smart" nanofertilizers, which can react to environmental signals like pH or temperature (G. Sharma et al., 2019). In order to promote sustainable farming practices, this method can decrease nutrient losses and increase the efficiency with which plants use nutrients.

Adding nanosensors to nanofertilizers might make it possible to monitor soil nutrient levels in real-time, which would lead to more accurate application and less nutrient loss. Increased crop yields with less pollution are possible because to this technology's ability to assist farmers in applying fertilizer at optimal times (Zulfiqar et al., 2019a).

To further guarantee their safe and effective usage, research should also focus on comprehending the possible hazards of nanofertilizers to human and environmental health and on creating transparent regulatory frameworks and standardized protocols. To make sure they are safe for humans, crops, and soil organisms in the long run, researchers need to look at how hazardous nanofertilizers may be. Finally, spreading information about the benefits, safety, and effective use of nanofertilizers is crucial in order to encourage their acceptance and use in agriculture. This can be accomplished through education and outreach programs that target farmers and other stakeholders (Murgueitio-Herrera et al., 2022b; Zulfiqar et al., 2019b). Drones equipped with cameras for precision agriculture may take multispectral images of the field, revealing the concentration of nutrients. This helps farmers to save valuable resources by preventing over-or under-application of fertilizer. For the sake of agricultural land sustainability in the long run, research into the potential hazards and advantages of using nanofertilizers should be prioritized. However, there are production economics and environmental costs, possible ecological repercussions, and yield advantages to consider when producing and employing these molecules to enhance food production with enhanced nutrient efficiency. Therefore, a comprehensive review of nanoparticles' use might be provided via a life cycle assessment that takes into account their impact on yield productivity, environmental consequences, and food chains. Verifying the pros and cons of nanofertilizers in practical field settings to allay stakeholder fears is another unresolved issue that stands in the way of their broad deployment.

11. Conclusion

In summary, the application of state-of-the-art nanotechnology to agriculture offers a viable solution to the worldwide problem of raising food production while preserving the environment. Through targeted nutrient delivery, nanofertilizers have the potential to improve plant growth and increase agricultural yields, as highlighted by the literature review included in this article. Through the classification of nanofertilizers into groups centered on enhancing plant growth, nutrient inclusion, and micronutrient delivery, we have been able to obtain a better understanding of their wide range of uses and efficiency with respect to different plant species.A thorough knowledge of the use of nanofertilizers in sustainable agriculture may be obtained by carefully examining their chemical composition, particle size, concentration levels, and plant species and growth promotion strategies. Furthermore, the investigation of potential avenues for future study and unique research requirements emphasizes how crucial it is to keep coming up with new ideas and working together to advance nanotechnology for agricultural applications.Prioritizing research efforts towards the development of nanofertilizers tailored to address specific nutrient deficiencies, such as macronutrient nanofertilizers containing nitrogen and phosphorus, is imperative as we navigate the challenges of feeding a growing population while minimizing environmental impact. By doing this, we may support the preservation of ecosystems and natural resources in addition to increasing agricultural output. This study essentially promotes the strategic application of nanotechnology in agriculture to meet the goals of environmental sustainability and food security. Currently, a more resilient and fruitful agricultural system and research that satisfies the demands of both current and future generations can be achieved by using the potential of nanofertilizers.

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