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Nano Fertilizer in Crop Production: The Changing Scenario

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

While the world's population is growing exponentially, there is an alarming increase in the need for food, which might reach a record nine billion people by 2050. In order to address the issue of rising food demand, a number of initiatives are being put into place to boost crop output and safeguard them against agricultural pests. The growing population pressures agricultural civilization to develop fresh strategies for boosting crop output. For nations all across the world, the issue of poverty and malnutrition has grown to be of great concern. Progress in the agricultural sector, which provides the raw materials for the food and feed industries, is crucial for both economic development and population expansion. With economic development, the soil nutrient balances are differed. Soil

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fertility is important in developing countries for assisting the economy and agriculture. There is a high demand in the twenty-first century for efficient, reliable, and cost-effective systems for detecting, supplying, monitoring, and diagnosing biological host molecules and nutrients. Traditional farming methods are incapable of keeping up with the rate at which food needs are increasing, so we must rely on and incorporate nanotechnology in agriculture and related sectors. In modern agriculture, increasing agricultural productivity is impossible without the use of chemical fertilizers and pesticides; however, the majority of agrochemicals are not eco-friendly and are thus harmful to human health. Nanotechnology is a novel technique for improved and sustainable agricultural production and also harbours a good capacity to bring novel alterations in the agricultural systems. Nanotechnology introduces new technologies and materials for use in molecular biology for the identification of plant pathogenic microorganisms. By bringing novel methods for distributing nutrients through nano fertilizers, specialized pathogen-targeted treatment, and boosting plant pest-resistance, nanotechnology has the potential to change the agricultural industry. Moreover, it can increase plants' ability to absorb nutrients and to endure environmental stresses. The fertility of the soil is a key factor in helping the economy and agriculture in developing nations. The benefits of strategies using nanotechnology for sustainable agriculture are covered here.

Keywords: Pathogen-targeted treatment; nanotechnology; agricultural civilization; nano fertilizers.

1. INTRODUCTION

1.1 Scope and Importance of Nano-Fertilizers

“In general, the use of modern agricultural inputs in the second half of the twentieth century increased agricultural production in the majority of countries. At the same time, agricultural production has faced new challenges. Nonetheless, new technologies have been developed around the world to address production constraints and sustain farm production. In this context, nanotechnology has a greater role in crop production, with a strong promise to replace fertiliser use with environmental safety, ecological sustainability, and economic stability” [1,2]. “Because of the increasing challenges in Indian agriculture, scientists have turned their attention to nanotechnology with the goal of increasing crop productivity and resource use efficiency. Researchers created nano particles with a high surface area, high activity, a better catalytic surface, a rapid chemical reaction, rapid dispersibility, and a large capacity for water absorption and retention. Nano particles, a product of nanotechnology, can be used throughout the agricultural production system value chain” [3].

For the research community, nanoscience and nanotechnology represent a new frontier. “Nanotechnology works with the smallest particles possible, raising hopes for increased agricultural productivity by solving problems that have previously been unsolved. The goal of nanotechnology is to create novel materials and devices with nanoscale features, drawing on fields such as applied colloidal science, physics devices, and supramolecular chemistry. Crop improvement in agriculture is a continuous process. In terms of management, efforts are being made to improve the efficiency of applied fertiliser through the use of nano clays and zeolites, as well as to restore soil fertility through the release of fixed nutrients. Controlling nutrient release and availability, characterization of soil minerals, weathering of soil minerals, nature of soil rhizosphere, nutrient ion transport in soil plant system, emission of dusts and aerosols from agricultural soils and their nature, soil and water conservation, water treatment and efficient management, soil and water pollution remediation, and precision farming are all potential applications” [4].

The term “Nanotechnology” was first used by Norio Taniguchi in 1974. The word “Nanotechnology” has originated from a Greek word ‘nanos’ which means “dwarf”. Nanotechnology is defined as understanding and control of matter at dimensions of roughly 1-100 nm, where unique physical properties make novel applications possible [5].

“Nanoparticles: Nanoparticle is defined based on the size at which fundamental properties differ from those of the corresponding bulk material” [6]. “Nanoparticles overlap in size with colloids, which ranges from 1 nm to 1 mm in diameter” [7]. Novel properties that differentiate nanoparticles from the bulk material typically develop at a critical length scale of under 100 nm. The “novel properties” mentioned are entirely dependent on the fact that at the nano-scale, the physics of nanoparticles mean that their properties are different from the properties of the bulk material.

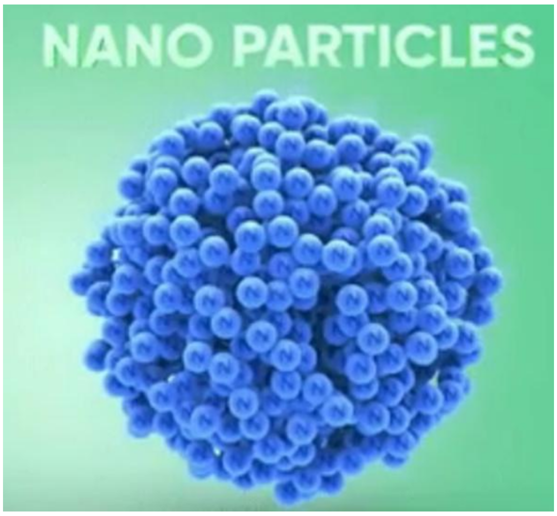

Fig. 1. Nanoparticles

“More importantly, the size dependent qualities, high surface volume ratio, and unique optical properties of the nano formulated nutrient elements hold great promise for application in plant nourishment. Because of their high surface area to volume ratio, nano-fertilizers may outperform even the most innovative polymer-coated conventional fertilisers, which have seen little improvement in the last decade” [8]. “Nano fertilisers with nano-formulated particles can directly supply essential plant nutrients to the rhizosphere at the time and dose required by crops” [9]. These results in higher input efficiency and less environmental impact than traditional fertilizer materials

Fertilizers have been used for the past many years in agriculture for the benefit of farmers. Traditional fertilizers are expensive as well as harmful to human beings and the environment. Therefore, there is a need for developing environment-friendly fertilizers having high nutrient value as well as compatibility with soil and environment. Nanotechnology is rising as a promising alternative in the form of nanofertilizers to enhance the qualitative attributes therein. A nanofertilizer comprises nanoformulations of nutrients deliverable to plants, enabling sustained and homogeneous absorption. Previous researches have shown that nanofertilizers enable plant productivity to increase the nutrient usage, reduce soil toxicity, mitigate possible adverse effects of excessive use of chemical fertilizers, as well as fertilizer application frequency. Moreover, the use of nanofertilizers drastically reduces waste, thereby saving money and protecting the environment. Furthermore, nanofertilizers, along with beneficial microbes, i.e., nano-biofertilizers, have set a paramount application toward sustainable agriculture. The eco-friendly products have been expected to reduce the usage of conventional fertilizers by 50%. Although nanofertilizers have a lot of advantages, their consequences during and after application should always be carefully examined and kept in mind to make them more advantageous [10].

Types of Nano fertilizers

Nanofertilizers have been classified into three groups:

(1) Nanoformulation of micronutrients,
(2) Nanoformulation of macronutrients, and
(3) Nutrients-loaded nanomaterials [11].

Out of the three categories, nanomaterials or nanocarriers of nutrients are more popular as compared to nanomaterials made up of nutrients. The benefit of using nutrients-loaded nanomaterials is that they are safe to workers and environment friendly. Moreover, fertilizers encapsulated in the nanocarriers can release fertilizers in a precise manner according to the requirement. Various kinds of nanomaterials have been used for encapsulation and controlled release of fertilizers, such as polymeric nanoparticles, carbon-based nanomaterials, nanoclays, mesoporous silica, and other nanomaterials [12; 13 & 14]. Controlled-release nanocarriers have also been employed for many other applications, including pesticides, food, and drug delivery.

Advantages of nanofertilizers

1. Facilitate higher nutrient use efficiency:
    - ❖ Small particle size than pore size of root and leaves leads to more penetration into the plant
    - ❖ Improve uptake and nutrient use efficacy of crop plants
    - ❖ Prevent the loss of nutrients

2. Nutritional value and health:
    - ❖ Nanofertilizers enhance growth of plant parts and metabolic process such as photosynthesis; improve the yield

- More availability of nutrients helps to increase the quality parameters of crops, such as protein, oil content, sugar content, etc.
- More availability of nanonutrient to the plant, prevent from disease, nutrient deficiency and other biotic and abiotic stress, which result in better yield and quality food products for human and animal consumption

3. Controlled release

   - Nanofertilizers control the speed and dose of encapsulated nutrient/fertilizers to make more uptake by crop plant.
   - Increase availability due to slow release of nutrients
   - Increase actual duration of nutrient supply

4. Reduce lose and demand of fertilizers

   - Nanofertilizers can take up by the plants due to slower rate of release
   - Nutrients can be taken up by plants without wastage by leaching and/or leaking
   - Reduce the demand for fertilizers

5. Improve soil quality

- Improve water-holding capacity and soil quality
- Increase microbial activity

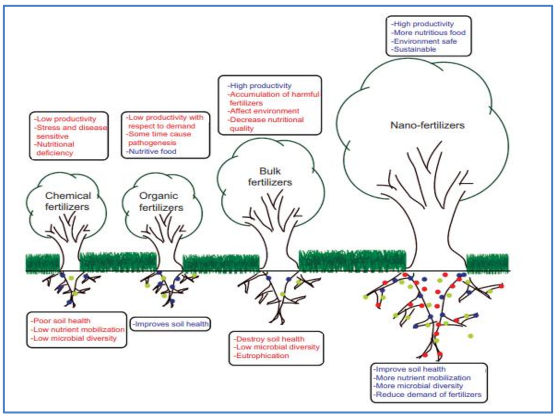

Fig. 2. Advantages of nanofertilizers

In this context, the use of nano fertilisers is expected to increase input efficiency, increase rice productivity, and alleviate environmental concerns. The development of nano-fertilizers (liquid) for agricultural use by private sectors has a good chance of meeting the challenge of precisely providing nutrients for plants through a more efficient nutrient delivery system. At the same time, it is critical to comprehend its effectiveness and advantages over traditional fertiliser materials. This is critical for reducing chemical fertiliser use and increasing nano urea without compromising crop yield.

2. MACRONUTRIENTS

2.1 Nitrogen Nano-Fertilizer

The chemical nitrogen is crucial for plant cells. The primary component utilised by plants to obtain sugars from water and carbon dioxide is chlorophyll (i.e. photosynthesis). Amino acids are essential components of proteins and serve as their building blocks. In plant cells, some proteins serve as structural building blocks, while others function as enzymes to catalyse chemical reactions. Energy-transferring substances like ATP, which enable cells to store and utilise energy, are largely composed of nitrogen. Proteins like DNA, the genetic material that enables cells to develop and reproduce, are largely composed of nitrogen. There are three different types of nitrogen: nitrate (NO3-) ions that plants can absorb, ammonium (NH4+) ions, and organic nitrogen molecules. The soil does not totally release the majority of the nitrogen. This is due to the extremely low likelihood that negatively charged nitrate will adhere to soil particle surfaces. Researchers experimented with different coating materials, such as polyurethane resin-coated urea, neem-coated urea, and sulphur-coated urea, in order to address issues related to nitrogen leaching during fertilizer application. Slow-release fertilisers are excessively expensive and take longer to release nitrogen [15].

2.2 Phosphorus Nano-Fertilizers

A typical important element for plants is phosphorus. A necessary nutrient, phosphorus influences the transit and storage of molecules in the plant cell. In the transport of energy within cells, phosphate plays a crucial role. By providing structural elements like phospholipids and phosphatides, phosphorus plays a crucial role in metabolism. The development of reproductive structures depends on phosphorus supply during the early stages of crop production. Some specific growth factors that have been linked to phosphorus include root growth stimulation, stalk and stem power enhancement, greater crop maturity, more uniform its and more resistant to plant diseases, and higher levels of positive N fixation. [16]. Research was done to determine the potential for delivering fertiliser by examining the cation exchange and solubility in mixes of rock phosphate, NH4+, and K-saturated clinoptilolite. Zeolites have been discovered to increase the solubility of phosphate rock when they are saturated with monovalent nutritional cations, such as NH4+ and K+. The performance of phosphorus fertiliser consumption ranged from 18 to 20 percent for different crops. The remainder, between 78 and 80 percent, is added to the field soil P tank and released to the crop during the following months and years [17]. The P releases for solid KH2PO4 were 52.5% and 58.9%, 55.7% and 80.6% for surfactant-modified zeolite (SMZ), and 90.5% and 71.5% for unmodified zeolite. Findings indicated that it is capable of physically adsorbing phosphate fertiliser [18]. The study revealed that SMZ was a potent sorbent for PO43- and that the release of P could be managed. According to SMZ characteristics, it would make a good slow release agent for fertiliser. It is simpler to water plants with mineral solutions comprised of natural minerals than with regular tap water to increase plant growth. [19]. The phosphate can have an impact on soil's biological and chemical composition as well as plant growth. By adjusting the proportion of primary phosphate solution to zeolite, the rate of phosphate release can be controlled. When ammonium ions change into nitrate, the lower of pH also causes calcium to be released from the rock. A plant that produces nutrients and phosphates using zooponic technology releases PO43- and other nutrients through the dissolution of phosphate and synthetic apatite. The zoopeinics delivered NPK when plants required it. Ion exchange and dissolving processes both contribute to the mechanism. The mobilisation of organic, inorganic, and fertiliser that has been "recharged" by the addition of water depends heavily on soil microbes. Zeoponic systems actually improve nutrient retention [20].

2.3 Potassium Nanofertilizers

Though not all of the processes in which potassium is essential have been discovered, it plays a key role in many of them. The activation of roughly sixty distinct enzymes by glucosinolates is known. Potassium deficient plants are more sensitive to heat, drought, and excess moisture. With the right amount of potassium, they are less prone to being attacked by pests, pathogens, and nematodes. Potassium is frequently described as a nutrient having distinct physical characteristics, including height, shape, colour, flavour, shelf life, fibre content, and more. Certain naturally occurring zeolites have significant amounts of exchangeable potassium, which promotes plant development. For instance, Some quantitative information on the K-zeolite slow release effect [21]. Applying 625 kg ha^{-1} of fertiliser combined with zeolite boosted the soil's potassium content [22]. Due to their size and the presence of negative charges, zeolites are essentially K-selective [23]. The only element that has reduced from soil, according to the author's premise, is potassium. It is hypothesised that the constant release of K from zeolites has the advantage of simultaneously supplying additional nutrients to plant roots.

More dissolved nutrients should be added to zeolite to "refresh" it. The relative order of their preference for ion exchange on zeolite was potassium (+) > sodium (+) > calcium (+) > magnesium (+) > ammonium (+). In order to test the efficacy of slow-release potassium fertilisers [24]. Nanotechnology can help to further boost the abundance of potassium in soil without relying on chemical fertilisers [25].

2.4 Secondary Nutrients Nano-fertilizers

The secondary nutrients calcium, magnesium, and sulphur are crucial and must be present in high concentrations for proper crop development. Certain plant species have higher phosphorus requirements than other plant species. When it comes to soil sulphur reactivity, an organic or microbiological process is the predominant reaction. Since them both interact with soil clays, Ca2+ and Mg2+ behave similarly to potassium. Tricalcium silicate was found to be a slow-release fertiliser for calcium and magnesium [26]. They assert that zeolite raises the amounts of calcium and magnesium in the soil.

Zeolite can exchange ions such as calcium and magnesium, [27]. Surfactant-Modified Zeolite (SMZ), according to batch and column investigations done in 2010, may function well as a sulphate transporter. If we utilise the SMZ fertiliser as fertiliser additions, the leaching of sulphate is considerably decreased, and the progressive release of sulphate can be achieved. Due to the lack of research, biological secondary nutrients are typically disregarded.

The experiment was conducted batch and column tests that suggested SMZ, or surfactant-modified zeolite, can be an effective sulphate carrier. If we utilise the SMZ fertiliser as fertiliser additions, the leaching of sulphate is drastically decreased and the slow release of sulphate can be achieved. Due to the lack of research, biological secondary nutrients are typically disregarded [28].

2.5 Micronutrients Nano-Fertilizers

The nutrients known as micronutrients are those that are required in much smaller amounts than vitamins and minerals. Boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), zinc (Zn), chlorine (Cl), and nickel are micronutrients (Ni) Micronutrients are essential for healthy plant growth and effective crop production, despite the fact that they are only required in trace levels. In many Asian countries, the climate has a negative impact on the availability of micronutrients. Low crop yield and quality, uneven plant structure, fewer xylem vessels, disease and pest infestation, decreased productivity, and the administration of seven key nutrient fertilisers are some of the negative effects of micronutrient deficits in plants [27]. Attempted to describe the varied natural zeolites' and bentonite's ability to bind and release zinc and iron [29]. To ascertain the likelihood of these ions solubilizing, the Langmuir and Freundlich equations are also utilised. According to the findings, natural zeolites have the potential to serve as carriers for slow-release fertilisers. The mineral's limited solubility and the exchange's sequestration effect are to blame for the sluggish release of Zn. As a result, plants can more easily absorb the discharged ions [30]. During three years, they investigated the effects of foliar applications of ion-exchanged zeolite on winter wheat. Zinc-zeolite had a stronger impact than copper-zeolite. Zeolite in the soil can improve plants' uptake of trace nutrients. The presence of neutral soil has boosted the release of cationic micronutrients. The concentration of P-rock, the soil, and the experimental procedure using different sources of $NH4+$ ions all had a significant impact on the concentration of Cu and Mn in Sudan grass. Ryegrass roots can be penetrated by zinc oxide nanoparticles, which improve germination. Using pumpkin plants as their test subject [29], A well-known experiment to show how carbon coatings affect plant cells. A clever nutrient transfer system in plants can be derived from this [31]. The zinc-rich ZnO nanoparticles (NPs) may raise the concentration of IAA in root sprouts, which in turn would suggest a faster rate of plant growth. Even though it is a crucial nutrient for plants, large amounts of boron can be toxic to some species. The adsorption of boron by minerals and soils has been the subject of numerous studies. Nitrate reductase enzyme utilises molybdenum. Mo plays a significant role in nitrogenase, a bacterium that fixes nitrogen and is crucial for legume crops [32].

3. NANO FERTILIZERS IN CROP NUTRITION

Particularly following the introduction of high yielding and fertiliser responsive crop types during the period of the green revolution, fertilisers have played a critical role in improving the food grain production in India. In spite of the overwhelming success in grain output, it has been seen that yields of many crops have started to plateau as a result of uneven fertilisation and a loss in the organic matter content of soils. In addition to harming aquatic habitats, excessive nitrogen fertiliser use also has an impact on groundwater. The utilisation efficiency of fertilisers is 20–50% for nitrogen and 10–25% for phosphorus, which is a worrying statistic. The nutrient buildup in soils, which causes eutrophication and taints drinking water, may be prevented by the use of nano-fertilizers, which are gaining popularity as alternatives to conventional fertilisers. In actuality, advances in nanotechnology have created new possibilities for enhancing nutrient utilisation effectiveness while lowering environmental protection expenditures. Recent discoveries showing plant roots and microbes can directly lift nutritional ions from the solid phase of minerals have been made public. Nanocomposites and nano-fertilizers with slow release are good substitutes for soluble fertilisers. Throughout the growth of the crop, nutrients are released more slowly, but most of them can be absorbed by the plants without going to waste. Zeolites, a class of naturally occurring minerals with a layered, honeycomb-like crystal structure, can be used to gradually release nutrients into the environment. Nitrogen and potassium can be added to its network of interconnecting tunnels and cages, along with other slowly dissolving components that also contain phosphorus, calcium, and a whole range of minor and trace nutrients. The slow and constant release of nutrients can be facilitated by coating fertiliser particles with nanomembranes. Although incredibly revolutionary, nano-fertilizer technology has received little attention in the literature [33].

“The nanofertilizers have an extraordinary potential to improve food quality, worldwide crop productivity, plant assurance, identification of crops and animal health, monitoring of plant growth, pesticide, herbicides, and fungicides” [34].

By giving the nutrients in the form of nano-fertilizers, the quality of plant nutrition may be ensured. a. "Nanoparticle" components are present in the nanostructured carriers. To improve their efficiency, enzymes can be added to an absorbent substrate such chitosan, polyacrylic acid, clay, or zeolite. b. Using the required nutrients in nanostructured-based therapies (either in suspension or encapsulated form), the issue may not necessarily be the amount of necessary components in the soil. Yet, there are issues with planting material distribution. The encapsulation of microfertilizers in nanomaterials is the subject of experiments. Examples include synthetic zeolites, Montmorillonite nanoclays, silicon nanoparticles, clay nanoparticles made of urea, porous and mesoporous silica, and metallic nanotubes [32].

The microscopic size of the nano-fertilizers makes them effective in supplying sites for plant food processing, while having a high surface area boosts their action [19]. This leads to greater plant development while using fewer vital nutrients. They are incredibly water soluble. The penetration rate of micro-nanos is increased in the plant system due to the very small particle size of nano-fertilizers (less than 100 nm). The surface area of plant roots and leaves is smaller and has a higher surface area than nano fertiliser particles. This enhances the penetration of the applied surfaces into the plant system, increasing the bioavailability and use of the nano-fertilizers. fewer particles per unit surface area, smaller particle size.

Although fertilisers are crucial for the growth and development of plants, the majority of applied fertilisers are inaccessible to plants due to a variety of processes, including leaching, photolysis, hydrolysis, and decomposition. Although micronutrients are present in very small quantities in both soil and plants, they play an equally significant role as primary or secondary nutrients. Six elements, namely iron, manganese, zinc, copper, boron, and molybdenum, are crucial micronutrients [35 & 36].

Having a large surface area and particles smaller than the pore size of plant leaves, nano fertiliser can more effectively penetrate plant tissues from the applied surface, increasing uptake and nutrient use efficiency [37 & 38].

4. NANO-FERTILIZER IN RICE

The negative consequences of nanoparticles are also emphasised in this review. According to several studies, the combination of nanoparticles in a safe dose can promote crop growth and development [39].

The recommended treatment combinations include a base application of RDF and two sprays of nano urea at key stages in two different doses (2% and 4%). According to the findings, nanospraying produced a better yield of rice grains (15–21%) than NPK addition using chemical fertilisers. Due to the enhanced availability of N within the plant system, the higher concentration of nano spray (4%) had a substantial impact on the plant development and yield indices. Although the overall cost of nanospray was more expensive than NPK addition, it produced a yield that was 12–16% greater than RDF addition, providing an extra financial gain (Rs. 7,937 to 10,082). Moreover, the greater effectiveness of nano urea led to a 25–34% reduction in the need for nitrogen fertiliser. At the same time, nano urea did not significantly alter the soil's characteristics or the microenvironment around the soil's roots [40].

When the nano urea (liquid) is sprayed on leaves at critical crop growth stages, nano urea easily enters through stomata and other openings and is assimilated by plant cells. It is easily distributed from source to sink within the plant as needed via the phloem [40].

“The application of nano urea on rice production resulted in unutilized nitrogen being stored in the plant vacuole and slowly released for proper plant growth and development. It was also found that using chemical fertilizer (NPK) at 100% RDF increases the height, shoot, and root length of rice plants. Simultaneously, the use of nano urea (spray) in conjunction with fertilisation (NPK) had a significant impact on growth parameters, particularly during critical periods” [40].

"Increased nano spray concentration (4%) had a significant impact on plant growth parameters due to increased N availability within the plant system. As a result, the nano spray assisted the rice excess mineral N applied via chemical fertiliser as it is used in the plant system. This is due primarily to the controlled release of nano nitrogen" [41]. The use of nano urea (spray) in conjunction with fertilisation (NPK) had a significant impact on growth parameters, particularly during critical periods. In summary, nano spray contributed to higher plant yield (15-21%) than NPK addition through chemical fertilisers alone.

"The primary reason for rice receiving two nano sprays performing better was because of nano pores and stomatal openings in plant leaves, which facilitated nano material uptake and penetration deep inside leaves, resulting in higher nutrient use efficiency (NUE). Precisely nano fertilisers have improved nutrient transport and delivery via plamodesmata, which are nano sized (50-60 nm) channels that connect cells" [42].

5. NANO-FERTILIZER IN WHEAT

Wheat grown with Nano-fertilizers Super Micro Plus spraying had higher biological yield and grain yield (NSMP). The NSMP treatment produced the highest grain yield, followed by the sole tri nano (N+P+K) treatment [43].

The wheat grain protein content (13.69%) was high under the treatment of nano super micro plus application and was comparable to the application of tri nano (N+P+K) fertiliser (13.33) when compared to other treatments. While the productivity of fertilisers achieved was significantly higher when treated with NSMP and Nano (N+P+K) (1936.0, 1581.0 Kg^{-1}) when compared to all other foliar feeding treatments, including the traditional one [43].

Nano-fertilizers are easily absorbed by the epidermis of leaves and translocated to stems, facilitating the uptake of active molecules and enhancing wheat growth and productivity [43 a].

The results of this study showed that there was a generally positive effect of combined nano N+P+K, N+P, N+K, P+K, and traditional NPK+TE nutrients supply on growth and yield parameters of wheat in Iraqi conditions when compared to the control [43].

6. NANO-FERTILIZER IN MAIZE

The maize grain yields differed significantly when 50% N was provided by urea and 50% N was provided by Nano urea in combination with Nano Zn, [44]. In conjunction with traditional fertilisers, nano fertilisers improve nutrient absorption efficiency. It increased productivity and grain output by enhancing photosynthesis and nutrient translocation.
The N: 80 P: 15 kg/fed produced the highest grain yield and biological yield. This application saved approximately 33.33% of mineral NP fertiliser, lowering pollution and fertiliser costs. The foliar application of nano micronutrient fertiliser (@ 200 g/fed) increased maize grain yield [44].

The grain yield increased by 10.45 and 14.40% when nano micronutrients were applied foliarly at 100 and 200g/fed, respectively, when compared to the control. This demonstrated that the use of nano micronutrient fertiliser significantly increased maize grain yield and its components. [45- 49].

Several studies found that using nano micronutrient fertiliser significantly improved maize growth traits. The use of zinc oxide nanoparticles increased plant height and dry matter weight [50]. Using Cu nano-particles increased maize plant growth by 51% when compared to a control [50]. Enhancement of leaf area, stem diameter, relative water content, and chlorophyll content due to application of complete nano-micronutrients (Fe, Cu, Zn, B, Mn) over the control [51]

7. NANO-FERTILIZER IN GROUNDNUT

The experiment was carried out at the College Farm, College of Agriculture, Rajendranagar, Hyderabad, to investigate the effect of Bio and Nano P fertiliser (soil application of bio and nano P @65 kg ha-1 and foliar application of bio and nano P @2 and 4ml l^{-1} and nano Phosphorus @1 and 2ml l^{-1} respectively) on yield, yield attributes, and quality of Groundnut (*Arachis hypogaea* L.) Phosphorus application at 40 kg ha^{-1} and application of bio and nano formulations increased the number of pods per plant, number of kernels per plant, and hundred kernel weight by 8.4%, 16.3%, and 19.4%, respectively, over control. Similarly, foliar application of nanophos at 65 kg ha-1 increased the number of pods per plant, number of kernels per plant, and hundred kernel weights by 6.6%, 14.7%, and 14.2%, respectively, over control, and this was followed by foliar application of biophos @4 ml l^{-1} and 2 ml l^{-1} [52].

8. NANO-FERTILIZER IN SUGARCANE

Maximum cane (83.7 tonne ha^{1}) and maximum sugar production (8.04 tonne ha^{1}) were obtained with 161 kg N ha^{1} supplied by Nano-Nitrogen Chelate Fertilizers (NNC) fertiliser [53]. With 80 kg N ha^{1} supplied from NNC and urea fertiliser, respectively, the lowest cane (59.3 tonne ha1) and sugar production (5.44 tonne ha^{1}) were obtained. Differences in sugar production between treatments are caused by differences in sucrose percentage and cane yield (fresh weight).

9. APPLICATION OF NANOFERTILIZER IN HORTICULTURAL CROPS

Vegetables: Productivity of a potato cv. Fertigation with nano NPK fertilisers could improve fertiliser and agronomic use efficiency in Arizona [54]. **Tomato** (*Lycopersicon esculentum*) Tomato (Lycopersicon esculentum) produced far more fruits per plant, fruit weight, and fruit diameter when 300 kg/ha K nano-fertilizer was applied, while 400 kg/ha K nanofertilizer produced the most plant height and stem diameter [55]. The cucumber crop received the largest fruit diameter when Ferbanat nanotechnology liquid fertilisers were applied at a rate of 3 L/ha [56]. The bio organic nanofertilizers prepared from cattle manure at 0.5 or 1 litre/ha at the start of intensive sugar beetroot development (BBCH 18 and BBCH 37-38) singly or twice. All treatments improved the photosynthesis process and sugarbeet productivity. In comparison to control plants, a 1 L/ha dose increased leaf number by 19.6%, leaf area by 13.4%, root diameter by 11.1%, canopy dry mass by 29.1%, root biomass by 42.6%, net photosynthetic productivity by 15.8%, root yield by 12.6%, sucrose content by 1.03%, and white sugar yield by 19.2% [57]. The effect of dwarfed long bean soil application of nano-fertilizer NPK 20:20:20 at 4, 8, and 12 kg/ha and commercial single fertiliser NPK 34:56:56 kg/ha [58]. Drumstick (*Moringa oleifera*) was treated with nano chelated iron at concentrations of 0, 1, 2, 3, and 4 mg/L, GA3 at concentrations of 0, 200, and 400 mg/L, and organic fertiliser Acadian at concentrations of 0 and 1 mg/L. At lower concentrations, nanofertilizer and GA3 had a positive effect on the production of -tocopherols, stigmasterols, and campesterol [59]. Iron 2 mg/L, nano iron 2, 4, and 6 mg/L, and control treatments were applied as foliar spray to Faba bean (Vicia faba L.) at three different stages: vegetative, before flowering, and during flowering. Protein percentage, chlorophyll content, and grain yield all increased as nano iron concentration increased. The highest grain yield was obtained with a nano iron spray of 6 mg/L. [60]. The yield and yield components of red bean (Phaseolus vulgaris L.) treated with N bio fertilisers increased. It was also discovered that K- chelate nanofertilizers could be used instead of chemical fertilisers [61]. The effect of nano iron chelate on the growth and yield of two spinach varieties, Varamin 88 and Viroflay [62]. According to the research findings, iron chelate nanofertilizers increased wet weight by 58 and maximum leaf area index by 47%. It demonstrates that nanofertilizer has a positive effect on all stages of plant growth and development. Cucurbita pepo L. cv. White Bush marrow treated with nano SiO2 had increased plant growth and germination, enhanced photosynthetic activity, reduced degradation, improved water use efficiency, and thus improved plant defence mechanisms and stress resistance [59]. The effects of nano-preparation on cabbage growth and nitrogen fertiliser utilisation efficiency [60].

10. CONCLUSION

The widespread use of agrochemicals to boost agricultural production has polluted not only the soil, groundwater, and food, as well as the environment. Increasing agricultural productivity is needed to satisfy food grain demand, but new approaches must be considered to minimise environmental damage. Nano nutrients are more efficient and cost-effective than conventional nutrients. The use of various types of nano-fertilizers has a significant impact on crop yield, natural resource protection, and crop fertiliser cost. The use of nano-fertilizers in agricultural fields will improve the quality of nutrient use. Nano-fertilizers promote good crop growth and yield through proper dosage and concentration. The future of nanofertilizers for sustainable crop production and the time required for their general adaptation as a source of plant nutrients are dependent on a variety of factors such as effective legislation, the production of novel nanofertilizers products as required, and associated risk management. There is an urgent need to standardise nanomaterial formulations and then conduct rigorous field and greenhouse studies to evaluate performance. Smart nanofertilizers with the ability to release nutrients as needed by plants in temporal and spatial dimensions must be developed for sustainable crop production. However, researchers and scientists must shoulder the responsibility of providing additional insights in order to fully utilise nanofertilizers for sustainable crop production under changing climate conditions without causing environmental pollution.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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