ajfand SCHOLARLY, PEER REVIEWED
AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
Volume 23 No. 7
July 2023
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

Afr. J. Food Agric. Nutr. Dev. 2023; 23(7): 23956-23974 https://doi.org/10.18697/ajfand.122.23145

NANOFERTILIZERS AS AN ALTERNATIVE TO INORGANIC FERTILIZERS: A REVIEW

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July 2023
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ABSTRACT

The population of the world is steadily increasing, in contrast to the natural resources which are limited and subjected to further depletion. This induces pressures to develop effective agricultural production systems to meet the growing demands on food and, thus, to mitigate hunger and poverty worldwide. Generally, inorganic fertilizers play a crucial role in maintaining soil fertility and improving crop yield and quality. Inorganic chemical fertilizers are regarded as the main source to supply crops with their needs of nutrients. Proper nutrient management of crops is a major challenge worldwide as it relies predominantly on chemical fertilizers. However, inorganic fertilizers are not only costly but may be harmful and pose risks to human health and have negative impacts on the environment. About half of the amount of applied fertilizers is used by the crop, whereas the remaining fertilizers are lost through leaching and gaseous emissions. The lost nutrients contribute to environmental pollution, global warming and climate change. Moreover, high application rates of chemical fertilizers can deteriorate soil fertility and raise soil salinity and thus lower crop production and quality will occur. This creates a need to invent smart fertilizers that are friendly to the environment, particularly those of high nutrient use efficiency and low leaching potential. Nanotechnology has a vital role in the construction of such fertilizers (nanofertlizers). In these fertilizers, nutrients are bound to nano-dimensional adsorbents (nanomaterials), which release nutrients very slowly as compared to conventional chemical fertilizers. Nanofertilizers are nutrients coated or encapsulated with different types of nanomaterials. They have unique properties like large surface area, slow-release profile, and controlled delivery of nutrients to the targeted sites to meet the nutrient requirements of crops. Nanofertilizers are emerging as a promising alternative to conventional chemical fertilizers, as they offer great opportunities to improve plant nutrition under harsh environments. The benefits associated with the use of nanofertlizers are opening new approaches toward the development of sustainable agriculture. However, further studies are needed for a sound and safe application of nanofertlizers. In this review, researchers' attempts to produce and use nanofertlizers for sustainable crop production have been presented. The advantages and limitations of the application of these smart fertilizers have also been discussed.

Key words: Nanoparticles, Sustainable agriculture, Phytotoxicity, Slow and controlled release, Metal oxides

https://doi.org/10.18697/ajfand.122.23145

INTRODUCTION

One of the major challenges facing modern agricultural systems is to satisfy current and future global food demands efficiently, while natural resources are depleting and the world population is increasing [1, 2, 3]. Worldwide food demand is anticipated to increase by 50 to 70 % in 2050 as the world population is expected to exceed 10 billion [2, 3, 4]. Climate change is projected to further impair the worldwide food production systems by causing injury to crops through inducing biotic and abiotic stresses [4].

Synthetic inorganic fertilizers, on the other hand, are indispensable for crop productivity improvement and significantly impact the food security of the world and without which, there would be only 50 % of the amount of food that is currently produced [1, 5]. However, the intensive application of conventional fertilizers over extended periods of time has caused serious environmental constraints including, greenhouse gases emissions, groundwater pollution, surface water bodies' eutrophication, soil quality degradation, and toxicity to beneficial living organisms [1, 6, 7]. These challenges call for the production of environmentally friendly and cost-effective fertilizers, particularly those with high nutrient-use efficiency and precision application. Nanofertilizers (NFs) are emerging as a promising alternative in the context of sustainable agriculture and climate change [3, 4, 6].

Nanotechnology is concerned with the study, design, creation, synthesis, manipulation and application of nanometric scale materials, having one or more dimensions with a length scale of 1–100°nm [2, 8]. Nanomaterials differ from their original bulk materials as they exhibit extraordinary chemical and physical properties. They represent the transition zone between the individual atom and their bulk counterparts. Subsequently, nanomaterials can enhance the release profiles, and efficient uptake of plant nutrients due to their small size, and high chemical reactivity because of their high surface area-volume ratio [1, 2].

There is a growing awareness to produce and use of NFs as a potential alternative for inorganic fertilizers to improve nutrient use efficiency and reduce environmental impacts. This is because NFs fertilizers have an extensive surface area, and contain macro and micronutrients to be released to crops in slow, steady and controlled release manners [2, 9]. In this respect, phyto-nanotechnology can be used to produce NFs with their improved delivery systems to enhance nutrient uptake, plant yield and quality, extend stress resistance, increase plant defense mechanisms, reduce wastage of fertilizers and lower production cost [1, 4, 5, 7, 8]. Nanofertilizers are very effective for precise nutrient management in precision

https://doi.org/10.18697/ajfand.122.23145

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agriculture as they release nutrients to the crop throughout the growing season in a controlled and prolonged fashion. They are regarded as the most desirable output of nanotechnology in the agricultural sector [3]. They provide a larger surface area for different metabolic reactions in the plant which increases the photosynthetic rate and yield of the crop [1, 3].

This review presents the recent attempts to utilize nanotechnology in agriculture to produce and use NFs as alternative smart fertilizers for inorganic fertilizers in crop production in the context of climate change and sustainable agriculture.

METHODOLOGY

The following issues have been addressed and reviewed based on the most recent related scientific articles: approaches of nanofertilizers (NFs) production, types of NFs, types of materials used in their production, methods of its application, advantages of NFs over inorganic fertilizers, and the role of NFs in sustainable agriculture. Besides, limitations and challenges that are associated with its production and application. Comparative studies have also been presented in the current review article.

Production of Nanofertilizers

Nanomaterials differ in chemical and physical properties from their original bulk materials. A wide range of materials such as metal oxides, ceramics and magnetic materials have been used to create nanoparticles. Nanomaterials or nanoparticles are usually used to produce NFs. There are several approaches or options to obtain nanomaterials and NFs:

1. ***The top-down approach:*** It is a physical method, starting from larger particles of the bulk materials to the nanometric scale [5, 6, 10, 11, 12, 13]. The limitation of this method is the low control in the uniformity and size of nanoparticles and a greater quantity of impurities.
2. ***The bottom-up approach:*** This approach begins at the atomic or molecular scale to build up nanoparticles using chemical reactions. It has the advantage of controlling the particle size and reducing the impurities in a better way [5, 6, 10, 11, 12, 13].
3. ***The biological (biosynthesis) approach:*** It is also called the green approach which is based on natural sources like plants, and microorganisms such as fungi and bacteria. The advantage of this method is the greater control of the toxicity and size of the particle [5, 6, 10, 11, 12, 13].

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For every application, the most recommended approach will require a synthesis capable of producing mass- scale particles with controlled physicochemical properties resulting in a homogeneous and target-specific nanoformulation. However, the challenges are diverse, such as the reduction of energy costs, better yields and the synthesis of a material with high efficiency. With the integration of these characteristics, it is possible to manufacture nanofertilizers that present high-performance and sustainable applications [10]. Bottom-up is in most cases the most effective approach used nowadays for NFs production [6].

Types of materials for nanofertilizers production

Nanomaterials are used to control the release of the fertilizer such that the nutrients are taken up only by the plant, and not lost to unintended targets like soil, or water [14]. Nanofertilizers can be produced from organic or inorganic nanomaterials [5, 6, 10] as follows:

1. ***Inorganic or metal-based nanomaterials:*** these nanomaterials use metal oxides, such as zinc oxide (ZnO), magnesium oxide (MgO), titanium oxide (TiO_2) and silver oxide (Ag_2O). Nanostructured nutrient carriers like nanoclays (zeolites) and hydroxyapatite are included in this category of nanomaterials [9].
2. ***Organic or carbon-based nanomaterials:*** These nanomaterials are composed mainly of carbon nanotubules and polymers. They are important plant growth regulators by stimulating seed germination, chlorophyll and protein contents [15].

Therefore, it is observed that there are several alternatives to produce NFs, making it necessary to choose the most appropriate method for each case and final application. The choice must be based also on the economic viability of the production and the performance of the final products.

This implies that there are numerous possibilities for NFs production. The choice of the method of production depends upon several factors. Minimum energy cost, better yield and the synthesis of materials with high efficiency, are the most important factors. However, the integration of these issues will make it possible to produce NFs with high-performance and sustainable applications. For example, the advantage of obtaining NFs via biosynthesis (biological approach) is the low toxicity of the final product. The other two methods of NFs production (physical and chemical approaches) and their limitations were discussed earlier. Besides that, NFs are produced from organic or inorganic nanomaterials depending on the type of crop, and the expected effect of NFs on that crop, as shown in Table 1.

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Types of Nanofertilize

Nanofertilizers are classified based on the nutrient categorization as:

1. ***Macronutrient nanofertilizers:*** Consist of one or more macronutrients of nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), sulfur (S) and calcium (Ca), combined with nanomaterials, or the nanomaterial itself is nutrient. Urea-coated hydroxyapatite NF, is an example and a rich source of N and P nutrients.
2. ***Micronutrient nanofertilizers:*** Micronutrients of zinc (Zn), boron (B), iron (Fe), manganese (Mn), and copper (Cu) have been combined with nanomaterials, or the nanomaterial itself is nutrient.
3. ***Nanobiofertilizers:*** Nanobiofertilizers are an integration of biofertilizers with nanoparticles to improve the growth of plants. Biofertilizers are formulations containing one or more microorganisms that can enhance soil productivity, by fixing atmospheric nitrogen (rhizobacteria), solubilizing phosphorus (arbuscular mycorrhizal fungi), or stimulating plant growth through the synthesis of growth-promoting substances. The use of nanoformulations can be helpful to enhance the stability of biofertilizers with respect to desiccation, heat, and UV inactivation [6, 9]. Table 1 shows several kinds of nanofertilizers, like nano macronutrients (N, P, K), nano micronutrients oxides (Fe, Zn, Mn), and others.

According to the type of formulation, nanofertilizers are also classified into three categories:

1. ***Nanoscale fertilizer***, which corresponds to the conventional fertilizer reduced in size typically in the form of nanoparticles. This category involves a top-down approach and is prepared by sizing down bulk materials. Nano-urea and nano-peat are some examples [2, 3, 15].
2. ***Nanoscale additive fertilizer***, which is a traditional fertilizer containing a supplement nanomaterial. This category involves the addition of a nanoscale material to existing macroscale traditional fertilizers to improve water absorption, retention, transport, cell wall extension, and soil stabilization. Carbon nanomaterials (nanotubes and nanofibers) are examples [2, 3, 15].
3. ***Nanoscale coating fertilizer/host fertilizer,*** refers to nutrients encapsulated by nanofilms. This category involves fertilizers that are adsorbed, entrapped, or encapsulated into the nano-pores, nanofilms, or within any type of nano-spaces of the host materials. The coated or encapsulated nanomaterials are rather better as compared to non-coated nanoparticles in terms of stability, slow release of nutrients, and bio-safety [3]. Controlled and slow-release

nanofertilizers are used to supply nutrients in a suitable concentration to plants over a prolonged interval of time, avoiding continuous fertilizer application, and reducing the environmental risks [2].

Methods of nanofertilizer application

Nanofertilizers can be applied by either the foliar or soil application [7, 14, 15]. Foliar application of NFs is preferred over soil application due to the significant enhancement of growth, yield, quality, physiological and biochemical traits [7]. However, studies are still being done to find out which method would be more efficient for nutrient utilization for different crops in different soil and the environmental conditions [5].

Nanofertilizers interact with plant cells wall that permits the entry of small particles through pores, where the exclusion limit is between 5-20 nm. They may also enter the cell via ion channels or endocytosis. The absorbed particles of NFs move through the apoplastic and symplastic pathways to reach the xylem and then spread to various plant parts by the vascular bundles [9].

Advantages of nanofertilizers

Nanofertilizer applications in agriculture may serve as an opportunity to achieve sustainability toward global food production. They have several advantages and important characteristics, for example, they have a very high specific surface area (surface area: volume ratio) and thus high reactivity. Thus, the bioavailability of nutrients will be increased and more sites will be available to facilitate different metabolic processes in the plant resulting in more photosynthates and dry matter production [1, 2, 3, 9, 10, 16, 17]. The particle size of nanofertilizers is less than pore size of leaves and roots of plants which can increase penetration into the plant and improve uptake and nutrient use efficiency [1, 9, 18]. Nanofertilizers may also provide the opportunity to the growers for supplying adequate amounts of micronutrients.

Besides that, nanofertilizers regulate the availability of nutrients in crops through slow, steadily, and controlled release mechanisms. Such a slow delivery of nutrients to targeted sites is associated with the covering or cementing of nutrients with nanomaterials. Thus, NFs may exert a positive role through slow nutrient release which leads to the efficient absorption and utilization of nutrients without higher losses due to the efficient nutrient management. The extended fertilizer release period reduces the risk of environmental pollution via reduced losses of nutrients to the environment, and hence NFs can be considered as smart nutrient delivery system. There are several studies indicating that NFs can release nutrients over longer periods of time, as compared to conventional fertilizers that release nutrients over shorter periods [1, 2, 4, 5, 6, 7, 10, 14, 17, 19]. For example, several investigators found that urea-modified hydroxyapatite nanoparticles encapsulated into cavities of the wood of *Gliricidia sepium* exhibited a slow, uniform and sustained release of nitrogen up to 60 days compared to a commercial nitrogen fertilizer which showed a non-uniform release of N only up to 30 days [20]. Depending on the soil pH, the released N after 60 days was 55 to 75% of the total N for the nanofertilizer, while that for the commercial fertilizers, was from 75 to 100% of the total N. They further indicated that the suggested nanofertilizer formulation can minimize the negative impacts on the environment by reducing nitrogen leaching, while maximizing the nitrogen use efficiency. The slow-release is according to plant demands and occurs by penetration through nanopores and stomatal openings in plant leaves [2, 8, 18]. The nutrients in the conventional forms of fertilizers are available to plants in ionic forms (soil solution). The ions being 100-1000 times smaller than NPs have higher chances of getting lost through leaching and runoff, or getting fixed in the soil, making them unavailable to plants. However, nano-forms of nutrients have fewer chances of fixation in soil due to size mismatch with lattice spaces and therefore higher uptake by crop plants. As an example, the ammonium ion (NH_4^+) that has a diameter of 2.8 Å which is close to the internal lattice space diameter of 2.89 Å of clay. These ions, due to this diameter similarity, get fixed into the clay lattice and become unavailable to the plants. Further, ions like nitrate (NO_3^-) are rapidly leached out from the soil and can contaminate groundwater resources. On the other hand, NPs are up to 100 times bigger in size than ions, and therefore they have lesser chances of being fixed in the clay lattice spaces and are less probable to be leached out from the soil [3].

Nanofertilizers, also, reduce the need for transportation and application costs [3, 13]. Therefore, decreases in greenhouse gas emissions (GHGs) due to NFs use would be expected [3]. As an instance, comparative studies, in a rice production system, indicated that a substantial reduction in GHGs with the use of nitrogenous nanofertilizers occurred. The investigations showed that the N_2O emission decreased from 1.67 mg m^{-2} day^{-1} by conventional ammonium sulfate usage to 0.88 mg m^{-2} day^{-1} by the N nanofertilizers use (nano zeolite-based N fertilizer formulations in nitrate and ammonium forms). About 50% reduction in the total GHGs in the form of N_2O and CH_4, due to the use of those nanofertilizer formulations, was recorded [3]. Moreover, the soil does not get loaded with salts that usually are prone to over-application using conventional fertilizers on a short- or long-term basis, due to using small quantities of nanofertilizers. Smaller amounts of nanofertilizers are enough to apply than synthetic fertilizers due to their small loss of nutrient nature [3, 6, 8, 12, 18, 19]. Thus, the cost would be minimized, and the profit would be maximized through using NFs [1, 14, 18, 19]. This implies that NFs would be attractive and affordable form economical point of view.

Additionally, NFs can be synthesized and delivered according to the nutrient requirements of intended crops; synchronizing the release of nutrients with crop needs, where the nutrients will be released from nanofertilizers when needed by the crop [7, 18]. Consequently, this will enable the plant to combat and eliminate various biotic and abiotic stresses [1, 4, 6, 10, 14]. They also have higher diffusion and solubility than conventional synthetic fertilizers [1, 12, 17, 19]. This implies also higher nutrient uptake of nanoparticles by plants by using various ion channels [3, 17].

On the other hand, polymer-coated NFs prevent premature contact with water and soil, and thus negligible loss of nutrients. They improve soil fertility and develop a favorable condition for microorganisms [1, 4, 8, 12]. This in turn, increases crop yield and improve nutritional quality [19, 21, 22]. Nanofertilizers can also improves crop growth and development due to their greater absorbance, high reactivity and ability to directly enter the cell through cell wall pores [7]. Compared with conventional inorganic fertilizers, NFs are less harmful to humans and the environment [1, 5, 7, 13, 18]. Furthermore, a reduction in the frequency of application and thus the soil toxicity linked to excessive application of inorganic fertilizers could also be minimized upon using NFs [5, 9].

It is also worth mentioning that there are several factors upon which the efficacy of NFs depends. The intrinsic factors like particle size and surface coatings are the most important issues influencing the efficiency of nanofertilizers application. Moreover, extrinsic factors, such as organic matter, soil texture or soil pH also strongly affect their potential effectiveness. In addition, the exposure route significantly influences the behavior, bioavailability, and uptake of NFs [6, 15].

Nanoferitlizers for sustainable agriculture

Several studies have revealed that nanostructured fertilizers have a crucial role in sustainable agriculture by improving crop productivity, quality and stress tolerance [6, 9, 13]. For example, it has been reported that the use of nanofertilizers can improve crop production by up to 30 % compared with traditional inorganic fertilizers [2]. Other investigators indicated that nano iron oxide (Fe_2O_3) increased growth and enhanced photosynthesis of soybean [16]. They also reported that the foliar application of nano iron oxide (0.5 g l^{-1}) at three growth stages of soybean induced 48 % increase in grain yield in comparison with control. Additionally, researchers also reported that nano hydroxyl apatite application to soybean induced higher seed yield (20 %) compared to regular P treatment. A new hybrid slow-release nanofertilizer synthesized by the incorporation of nanoparticles like zinc, copper, and iron into urea-modified hydroxyapatite was used on the ladies' finger crop to enhance the use efficiency of the fertilizer and nutrient uptake [22]. Others indicated that the foliar application of chitosan-NPK fertilizer resulted in a higher harvest index and a reduction in the growing season of the wheat crop compared to conventional NPK fertilizer [23].

Additionally, it has been reported that nano zinc oxide application in zinc-deficient soil caused improvement in nutrient use efficiency and enhanced the productivity of eggplants by 91 % than regular fertilizer [24]. It has also been shown that nano-sized hydroxyapatite application enhanced the growth rate by 33 % and seed yield by 20 % of soybean than the regular P fertilizer [25]. Furthermore, a study demonstrated that spraying of onion bulbs with ZnO NPs (20 and 30 μg ml^{-1}) three times at 15 days intervals resulted in better growth and earlier flowering than control [26]. Meanwhile, others indicated that treatment of groundnut with nanoscale ZnO (25 nm mean particle size, at 1000 ppm) showed an increment in crop yield (34 %) compared to bulk $ZnSO_4$ [5]. Moreover, many researchers reported that the yield of common bean and wheat crops was improved by the foliar application and seed priming of ZnO-NPs [27, 28]. Researchers have studied the effect of seed priming of wheat crop with ZnO NPs at 100 mg L^{-1}, which enhanced the grain yield by 185 % than control plants [28]. Others found that carbon nanoparticles improved the crop yield of the tomato crop, as it produced flowers and fruits two times more compared to plants grown in control soil [29]. It was also indicated that the foliar application of the Mn nanooxides (Mn_3O_4, 56 nm) recorded a significant increase in vegetative growth characters and yield of the squash crop [30]. Meanwhile, it was reported that the ZnO-NPs were more effective than regular $ZnSO_4$ in increasing the grain Zn content of wheat [31]. Investigators also reported that the use of the nanohybrid of polyvinyl acetate-starch, as a substrate for the slow release of copper and zinc nutrients, increased the yield of chickpea plants by 46 % to 96 % [32]. Some studies indicated that nanofertilizers increased nutrient use efficiency of crops up to 3 times [17]. It was also shown that foliar application of nanophosphorus at 640 mg ha^{-1} gave cluster bean and pearl millet yields equivalent to those at 80 kg ha^{-1} P application [21]. Others found that the ZnO NPs (< 100mg kg^{-1}) was more bioavailable to cucumber crop than their bulk counterpart [33]. Other investigators reported that the average gain in nanofertilizers effectiveness relative to conventional fertilizers was 20 to 30 % [34]. Researchers found that a foliar application of an eco-friendly nano-composite NPK (25 %) significantly promoted the growth and yield of red pepper as compared with the control and chemical fertilizer-treated plants [35]. Other studies showed that nanofertilizers of seaweed extract and amino acids were superior to the conventional fertilizer as they produced higher fruit weight, yield and fruit maturity percentage of *Khastawi* date palm cultivar [36]. This was attributed to the nanoparticles high penetration efficiency of cell membranes and thus higher nutrient availability, cell division and metabolism. Some studies suggested that tomato plants treated with urea coated with ZnO NPs exhibited a higher number of leaves and number of fruits set in comparison with non-treated plants [37].

The positive effects and benefits of different kinds of NFs on the agronomical properties of some selected crop yields are presented in Table 1. Other NFs with their beneficial effects on improving crop productivity are also presented by other researchers [12]. Several commercial NFs are freely available in the market by major chemical companies, like Nano Max NPK Fertilizer and Biozar Nano-Fertilizer [9]. Some approved and commercially available nanofertilizers have also been mentioned in other reviews, like Nano ultra-fertilizer, Nano calcium (magic green), Nano micronutrient (EcoStar), and NanoGro [12]. A significant improvement in wheat crop growth and yield, besides enhancement of Zn uptake and recovery efficiency, by seed coating with 1.5-3.0 % ZnO nanofiber under alkaline calcareous soil environment has been recognized and reported [38].

Limitations of nanofertilizers

The use of nanofertilizers in agriculture is associated with some disadvantages and limitations, which need special attention, and these can be summarized as follows:

1. Potential health risk: which is due to exposure to nanoparticles (xenobiotics) during nanofertilizers manufacturing and application in the field [4, 5, 6, 14]. Human exposure to Nanofertilizers can lead to serious health risks due to associated cyto- and genotoxicity aspects. Nanoparticles can enter the cell membranes to reach cytoplasm, organelles and even cell nucleus and can alter the gene expression [7]. Nanofertilizers may, also, be subjected to transformation into other more toxic species and impose risk to human health due to their high reactivity. For example, some researchers investigated the potential toxicity of CeO_2 nanoparticles using hydroponic cucumber seedlings and found that cerium NPs were subjected to different processes of reduction (Ce^{4+} to Ce^{3+}) and translocation via xylem and phloem with a significant implication concerning bioaccumulation of Ce in the food chain [39]. Exposure to ZnO NPs was evaluated and found that these NPs had the potential to exert cytotoxicity to humans represented by cellular damage at the mitochondrial and DNA levels [40].

https://doi.org/10.18697/ajfand.122.23145

2. Phytotoxicity: This is due to the bioaccumulation of nanoparticles in plants [5, 41]. The phytotoxic effect is dependent on species, dose, and application method as well as type of NPs (composition, size, shape, and surface properties) [6]. Nanomaterials have also a toxic effect on several soil microorganisms including bacteria, yeasts and fungi. Nanoparticles can easily enter cells, tissues, and organelles and affect functional biomolecular structures like DNA, and ribosomes [3, 8]. Nanoparticles can enter the food chain in non-targeted species and induce adverse environmental impacts. They can modify the DNA structure and gene expression in plant tissues. Iron-based nanofertilizers can alter the hydraulic conductivity of roots due to the accumulation of the applied nanoparticles on the root surface, which leads to a lowering of water and nutrients uptake [7]. In general, one of the major concerns with nanofertilizers is the potential toxicity caused to plants, microbes and animals [3]. Metal oxide NPs can cause nanotoxicity and genotoxicity to crop plants. There is also direct genotoxicity (where NPs directly damage the DNA), and indirect genotoxicity (ROS generation and NPs interaction with nuclear proteins) [42]. Some investigators also found out that Y_2O_3 NPs (>10 mgL^{-1}) delayed seed germination of tomato and inhibited root activity and elongation of hydroponic tomato seedlings [41]. They also indicated that Y_2O_3 NPs phytotoxicity was higher than their soluble form counterpart.
3. Uniform size of nanoparticles: the production of a uniform size of nanoparticles is also a challenge [8].
4. Lack of legislation, absence of rigorous monitoring, research gaps, and lack of long-term environmental impact studies under field conditions [8, 9, 10].
5. The cost of production at the industrial scale is considered an obstacle and roadblock and may delay switching to nanofertilizers [3].
6. The buildup of NPs in plant tissues without transformation or assimilation. This is especially important for crops where fleshy and leafy parts are consumed. For example, it was noticed the Ag NPs entrapment on leaves of lettuce by the cuticle and penetration through stomata in the leaf tissue [43]. Therefore, the type of crop can also be a limitation for the adoption of nanofertilizers, especially in vegetables where edible parts are directly exposed to fertilizers [3].

Current level of research at the country level

Nanofertilizers (NFs) research studies are very limited in Jordan. For example, there are two studies on NFs application. The first one is the "*Effects of nanotechnology liquid fertilizers on fruit set and pods of broad bean*". While the second one is: "*Effect of nanotechnology liquid fertilizers on yield and nitrogenous compounds of broad bean*".

CONCLUSION, AND RECOMMENDATIONS FOR DEVELOPMENT

In the current agricultural production systems, excess use of agrochemicals, conventional fertilizers, in particular, has polluted the soil, water and food. Increasing crop productivity is highly needed to meet the food demand of the ever-growing world population. However, the damage caused to the environment by the over-application of inorganic chemical fertilizers should be considered. Nanofertilizers have emerged as promising efficient alternative fertilizers to decrease the additions of synthetic fertilizers, and enhance crop productivity through the smart delivery of active ingredients. This is manifested through increased nutrient uptake, improved nutrient use efficiency, and decreased nutrients losses to the environment through volatilization, leaching and runoff. Nanofertilizers use is offering great opportunities to improve plant nutrition and stress tolerance to achieve higher yields in the frame of global climate change and sustainable agriculture. Nanofertilizers offer the best chance, at present, to reclaim the health of the ecosystems damaged due to the bulk use of fertilizers and mitigate climate change by committing to promising technologies. However, the risks associated with nanofertilizers use in agriculture should be carefully examined. It is necessary to investigate whether NFs are fully transformed into ionic forms and later incorporated into proteins and different metabolites or whether some residue remains intact and transferred to humans via the food chain. Therefore, further research studies are highly needed to assess the impact of nanofertilizers under different environmental conditions. Economic feasibility should also be evaluated.

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Volume 23 No. 7
July 2023
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

Table 1: The beneficial effects of some kinds of nanofertilizers on selected crop plants

#	Nanofertilizers	Crop	Effect on crop plant	Reference
1	Nano hydroxyl apatite (nHA)	Soybean	Induced higher seeds yield (20%) compared to regular P treatment	[1]
2	Nanoscale ZnO (25 nm mean particle size at 1000 ppm)	Groundnut	Increment in crop yield (34%) compared to bulk $ZnSO_4$	[5]
3	Nano iron oxide (Fe_2O_3)	Peanut	Increased growth and yield	[16]
4	Foliar nano-iron oxide (0.5 g l^{-1})	Soybean	48% increase in grain yield in comparison with control	[16]
5	Foliar application of nanophosphorus at 640 mg ha^{-1} (40 ppm)	Different crops	Increased nutrient use efficiency up to three times	[17]
6	Hybrid nanofertilizer (HNF) synthesized by the incorporation of nanoparticles (zinc, copper, and iron) into urea-modified hydroxyapatite	Ladies' finger	Enhancement of nutrients uptake and production of nutrient-rich fruits	[21]
7	Foliar application of chitosan-NPK fertilizer	Wheat	Higher harvest index and a reduction in the growing season	[22]
8	Nano zinc oxide	Eggplants	Improvements in nutrient use efficiency and enhanced the productivity	[23]
9	Spraying of ZnO NPs	Onion bulbs	Better growth and earlier flowering (12-14 days) than control.	[25]
10	ZnO NPs at 100 mg L^{-1}	Wheat	Enhanced the plant growth, and grain yield (185%),	[27]
11	Foliar application of the Mn nanooxides (Mn_3O_4, 56 nm)	Squash	A significant increase in vegetative growth and yield	[29]
12	ZnO-NPs	Wheat	Increasing grain Zn content and alleviating Zn deficiency in human diet	[30]
13	Nanohybrid of polyvinyl acetate – starch (copper and zinc)	Chickpea	Increased the yield by 46% to 96%	[31]
14	Nano-composite NPK (25% concentration)	Red pepper	Promoted growth and yield	[34]
15	Nano seaweed extract and amino acids	*Khastawi* date palm	Higher fruit weight, tree yield and fruit maturity percentage	[35]
16	Urea coated with ZnO NPs	Tomatoes	Higher number of leaves and number of fruits set	[36]
17	Seed coating with ZnO nanofiber	Wheat	Increase in plant height, biological yield, number of grains per spike, 1000 grain weight	[37]

https://doi.org/10.18697/ajfand.122.23145

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