Journal of
Food Chemistry & Nanotechnology

https://doi.org/10.17756/jfcn.2023-s1-053

Review Article

Open Access

Nanotechnology in Agriculture for Improving Crop Yield: A Review

Bhanuprakash HR[1*], Deepak R Sapkal[1], Malalu Hanumanthappa[2], HP Rajath[1], Sangeeta Pandey[1], Navinkumar[3], Vishwanth VE[1] and Soumya K[4]

[1]*Amity Institute of Organic Agriculture, Amity University, Noida, Uttar Pradesh, India*
[2]*Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences, Shivamogga, Karnataka, India*
[3]*Lovely Professional University, Phagwara, Punjab, India*
[4]*University of Agricultural Sciences, Bangalore, India*

***Correspondence to:**
Bhanuprakash HR
Amity institute of Organic Agriculture,
Amity University,
Noida, Uttar Pradesh, India.
E-mail: hr.bhanuprakash@gmail.com

Received: October 02, 2023
Accepted: November 03, 2023
Published: November 08, 2023

Citation: Bhanuprakash HR, Sapkal DR, Hanumanthappa M, Rajath HP, Pandey S, et al. 2023. Nanotechnology in Agriculture for Improving Crop Yield: A Review. *J Food Chem Nanotechnol* 9(S1): S420-S428.

Published by United Scientific Group

Abstract

In today's agricultural research, nanotechnology has taken the lead. Nano fertilizers are one of the most recent advances in the field of agriculture. These fertilizers are recent agricultural innovations, they can boost crop health, productivity, and food quality. Nano fertilizers release nutrients in the soil in a regulated, sustained manner and are highly effective and target oriented. It increases plant surface area for metabolic activities, speeding photosynthesis and agricultural yield, it also enhances direct nutrient uptake into the plant system and releasing fixed nutrients to restore soil fertility. It protects crops against biotic and abiotic stress, lowers cultivation costs, reduces fertilizer waste, and enhances nutrient usage efficiency. Studies suggest that nano fertilizers boost fertilizer efficiency, reduce soil toxicity, reduce overdosage risks, and release nutrients precisely. Foliar application is possible in poor soil and weather conditions. Nanostructured formulations can release active ingredients more precisely in response to environmental stimuli and biological demands through targeted delivery. Nano biosensors diagnose crop input demands in controlled environments and supply them on time and in the proper area. Nanotechnology enables new paths for agricultural research and has higher promise for sustainable agricultural practices, especially in developing nations like India.

Keywords

Yield, Plants, Efficiency, Nano fertilizer

Introduction

Nearly 6 billion people live in the world currently, with Asia housing 50% of them. Large number of farming community in Asian region were adopting and practicing modern agriculture practices for their livelihood, using large number of chemical fertilizers, herbicides, insecticides, fungicides. It causes more and more problems to our ecosystem in current scenario, lot of chemical usage leads to deterioration our natural resources and health of the soil and reducing productivity/fertility of soil by exhausting soil nutrients (macronutrients and micronutrients) by different ways and, we are losing beneficial soil flora and fauna. Over application of these chemicals without thinking on sustainability creates a long-term irreversible effect on our eco system by herbicidal resistance and decreasing efficiency of the applied inputs. The demand for adequate food incorporates the concept of sustainability in the modern day, which means that food must be available to both current and future generations. Concurrently, agriculture production ought to take place in a safe environment, free from exposure to potentially dangerous materials. However, to achieve high levels of productivity overall, intensive crop production requires additional plant nutrition, which can be provided either by soil application or foliar treatment. Although applying nutrients to the soil is the most popular method of nutrient delivery, it has issues with the plants' ability to access nutrients. Insoluble forms of inorganic nutrients are fixed in the soil, rendering them unavailable to plants and vulnerable to leaching by precipitation or irrigation water [1]. The exaggerated usage and application of lot chemical without thinking of future sustainability, it may lead to hawking situation in agriculture. Even though the world's population is expected to reach 10 billion by 2050, it has been proven that continuous chemical fertilizer application can meet both the growing population's need for food and the nutrient requirements of crops around the world. This is despite the poor uptake and large losses (sometimes as high as 70% for nitrogen and potassium and 90% for phosphorus) [2, 3].

The biggest worldwide challenge we have today is providing food stability for a population that is continuing to grow. For the burgeoning population, which by 2050 is predicted to total 9 billion people, various academics have predicted that the need for food will likely increase from 59 to 98%. However, there are several barriers to agricultural output currently due to soil erosion and climate change in many regions, which has negatively impacted the farming communities for the main source of income. A second round of green movement is needed throughout the country. The point of nanotechnology research is to completely revolutionize the world's food production systems. According to a recent assessment by the Food and Agricultural Organization, rapid urbanization and societal changes are also gradually depleting essential natural resources including arable and tillable land and water supplies (FAO). During the post-green revolution age, all these problems have grown to be significant barriers to the expansion of the agricultural industry [4].

This Nano fertilizer having ability to change the nutrient delivery system and enhance efficiency of the applied nutrients, it mainly by the increased surface area provided by nano fertilizers, it boosts the plant's metabolic rate, leading to faster photosynthesis and a higher dry matter accumulation and yield. Additionally, it triples the efficiency with which nutrients are used by the plant. Increased utilization of renewable resources is one of the environmental benefits of nano fertilizers. Soil aggregation and carbon uptake are both enhanced. Additionally, nutrients and growth promoters can be encapsulated into nano fertilizers for a delayed and targeted efficient release [5]. A few products, such copper-based (Cu) nano-pesticides used as fungicides and bactericide, have already been commercialized as the integration of nanotechnology in agriculture still in its infancy stage.

The application of nano fertilizers in soil has been shown to increase plant growth and improve seed germination in several studies, but the impact of these treatments on soil microbiota has received far less attention. Even though microbial communities are critical and sensitive targets for identifying the environmental dangers of nanoparticles. Current knowledge about the effect of nano fertilizers on the soil microbiome is limited. Exposure to 0.01 mg AgNP/kg in loamy soil for a year has been shown to have significant negative effects on soil microbial biomass (38.0%), bacterial ammonia oxidizers (17.0%), and the proteobacteria population (14.2%), while significantly stimulating acidobacteria (44.0%), actinobacteria (21.1%), and bacteroidetes (14.6%) [6]. Thus, it would be reasonable to predict that soil ecosystem activities including nitrification, organic carbon transformation, and chitin breakdown would be negatively impacted by the disturbance.

The most frequent method, applying nutrients to the soil, has significant drawbacks in terms of the nutrients' actual availability to the plants. Soil inorganic nutrients are both fixed in insoluble forms and leached away by precipitation and runoff [1]. Furthermore, nutrient intake is diminished by anything that inhibits root development, the use of a foliar spray can get around these restrictions. In addition, foliar feeding has been demonstrated as the quickest method of resolving nutritional deficits and boosting crop output and quality. In addition to limiting environmental damage and maximizing nutrient use with less use of fertilizer on the soil. Although cuticles on leaves permit gas exchange, it also limits the absorption of chemicals [7, 8]. Substances coated with nanoparticles, which have a size exclusion limit of 10 nm or less, can more easily pass through stomatal membranes. Nutrient utilization efficiency is improved, and the amount of active chemicals put into the plant system is decreased, because nanocarriers transport the nutrients precisely where and when they're needed. Research into the effects of nano fertilizers on crop development, growth, yield, quality, resistance to abiotic stress, and the mitigation of heavy metal toxicity is, in fact, required.

Characteristics that are exclusive to nanoparticles

- The outer layers of nanoparticles have a higher atomic density compared to their interior cores due to their small size. Consequently, the nanoparticles exhibit an elevated charge density and reactivity due to the substantial ratio of surface area to total volume.
- The behavior of the atoms on the surface of the particles becomes more important than their behavior inside the particles as the surface area grows in relation to volume. When particles are small enough in size, they begin to behave in a quantum mechanical fashion.
- The strength, heat resistance, melting temperature, and magnetic features of nanoparticles are strengthened as a result of the increased atomic contact inside intermixed materials, which can be attributed to their large surface-to-volume ratio.
- Atomic distribution across nanoparticles varies depending on their shapes and the exposed surfaces they have. As a result, the kinetics of electron transport between metal nanoparticles and their corresponding adsorbed species are altered.
- The sharp edges and corners of tetrahedral nanoparticles increase their chemical reactivity, making them more catalytically active than cubic or spherical nanoparticles.
- Except for hydroxy apatite, all the other nanoparticles had zeta potentials between +30 and -30 mv and exhibit a strong tendency to aggregate into larger particle sizes [9].

This review's primary objective is to describe most elements of nano fertilizers in depth, including their size features, applications, and advantages. A comparison of traditional fertilizers and nano fertilizers for nutritional types and benefits of their use is given.

Nanotechnology

The word "Nanotechnology" was first defined in 1994 by 'Norio Taniguchi' of Tokyo Science University. Nanotechnology refers to the field of study concerned with manipulating matter on the atomic and molecular scale, or "nanotech". Nanotechnology includes creating materials or technologies that fit inside structures that are between 1 and 100 nm in size [10].

What are nanoparticles?

- As a reference, you can think of a nanoparticle as a particle with at least one dimension that is 100 nm or less.
- A nanometer is one billionth of a meter (10^{-9} meters).
- A virus has a size of about 100 nm, which makes it simple to quantify.
- Here are a few illustrations to help you understand:
- There are 25,400,000 nm on an inch scale.
- The thickness of the newsprint is 100,000 nm.
- If marble were a nanometer, then one meter in the nano scale would be equivalent to earth size [10].

Nutrient requirements of plants

Nutrient management in agriculture is very crucial and critical to increase crop yields on a single piece of agricultural land with varied nutrient level pattern in soil. To meet crop needs throughout a crop growing season, soil fertility must be consistently high in order to meet demand.

When a crop is deficient in one or more of the nutrients required for proper growth and development throughout its life cycle, growth processes are inhibited, development is stunted, and deficiencies may be noticed. The ionic forms of elements were principal means of nourishment for plants. The phrase "criteria of essentiality" was first used in 1939 by Arnon and Stout. A criterion for essentiality was developed, and as a result, 17 nutrients are commonly identified as being necessary for plant growth and the completion of its life cycle. These fundamental nutrients are then split into two groups: There are two types of plant nutrients: (1) non-mineral nutrients, which are made up of the three elements Carbon, Hydrogen and Oxygen and make up about 95 per cent of a plant's dry weight and are taken in alongside carbon dioxide from the air and soil; and (2) mineral nutrients, which are largely absorbed from soil and comprise 14 elements, including the 3 primary nutrients nitrogen (N), phosphorus (P), and potash (K), manganese (Mn), boron (B), zinc (Zn), copper (Cu), molybdenum (Mo), chlorine (Cl), and nickel (Ni) are micronutrients; calcium (Ca), magnesium (Mg), sulphur (S), and iron (Fe) are secondary nutrients. These necessary mineral elements are absorbed from the soil in ionic forms. These minerals are further classified into three broad groups, depending on (i) essentiality (macronutrients and micronutrients, utilization, and absorption by plants), (ii) physiological function in plants, and (iii) mobility in soil and plants. These classifications are further divided into subcategories based on several nutritional essentiality criteria (Figure 1).

The fundamental 14 nutrients are required for better growth and development of rice plants. The initiation of panicles and grain development are largely influenced by N. Crops' ability to withstand disease and drought as well as maintain healthy root growth is aided by P. Potassium is crucial for plant metabolism, disease resistance, insect control, and stress tolerance [11]. Two secondary nutrients, Mg, and Mo are required for enzymes involved in the phosphate transfer and nitrate to nitrite reduction processes in soil, respectively. Cu and Fe are crucial components for photosynthesis. The creation of new plant cells, the expansion of flowers, and the germination of pollen all depend critically on the element B. Mn and Cl, which also help to activate a number of enzymes, help rice become more disease resistant. Sulfur helps with the synthesis of lipids and amino acids, but Ca is necessary for plant cell division [12].

Nano-based nutrients applied to crops may have advantages over conventional fertilizers, such as controlled and sustained release for a long period of time and delivery of agrochemicals in target, particularly nano fertilizers and nano pesticides, it decreases diseases and upholds food safety and security on a large scale [13].

Nanotechnology applications and usage in agriculture

Over the course of the past four decades, there has been a significant increase in the need for chemical fertilizers all over the world. This is due to the intensive agricultural production which has resulted in an increase in the quantity of nutrients that are extracted from soil. Between 1970 and 2008, there was more than 300% rise in the quantity of fertilizer needed to produce one ton of grain, as stated by several publications [14, 15]. It has been calculated that worldwide fertilizer use in 2013, 2014, and 2017 was 182.8, 186.7, and 199.4 Mt, respectively. According to research some of the nutrients were deficient in the soil those are phosphorous (P) 30 to 40 per cent deficit, Fe 30 - 50% deficit, N 59 per cent deficit and Zn 30 per cent deficit soil. This has a negative impact on agricultural productivity [16]. Notably, despite significant efforts over the past four to five decades, our nation's agriculture has maintained a dismal nutrient usage efficiency for N, P, and potassium correspondingly, 30 - 35%, 18 - 20%, and 35 - 40% [14]. Nanotechnology offers an alternate solution to some of the problems with conventional fertilizers, such as their reduced use efficiency and bulkiness. According to recent studies on nanotechnology, it offers various types of nanomaterial that are having one-of-a-kind or multiple roles in the agricultural sector, such as nano biosensors used in higher level precision agriculture for water and plant nutrient management, and nano herbicides application control weeds easily, its effective in weed management. Consequently, nanotechnology has more prospects in the agricultural sector because it is environmentally benign and uses sustainability [17]. Figure 2 shows the advantages of nano fertilizers for farming.

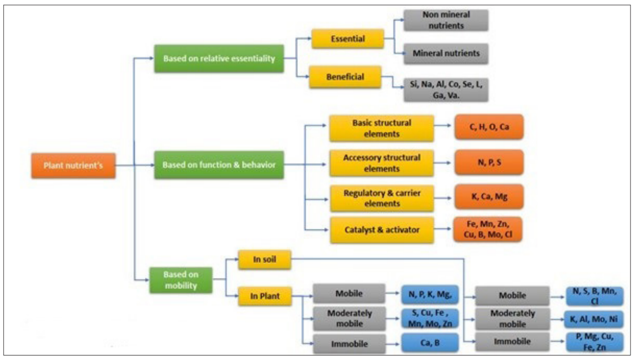

Figure 1: Plant nutrients details based on the relative essentiality, function, and mobility in soil and plants.

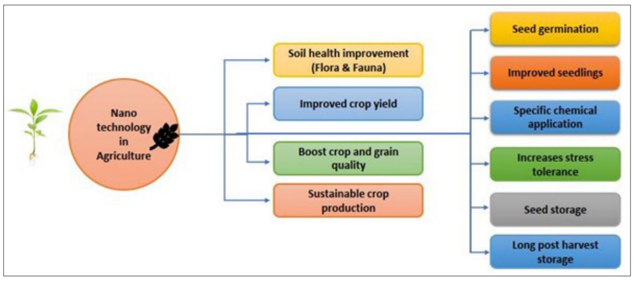

Figure 2: Advantages of nano fertilizers in agriculture.

The health, nutrition, and production of crops are profoundly affected by the accessibility of key nutrient components. Field tests conducted over a prolonged period have shown that nutrients intake from different commercial (conventional fertilizers) fertilizers can increase yields by 30 to 50% [18]. Recent studies by a wide range of scientists suggest that nanotechnology could intensely alter food production techniques around the world [4]. It offers a platform for agrochemicals that have an elegant delivery structure, are safe to use, are bound to a specific nutrient/chemical, and have an easy way of delivery. Nano fertilizers, which have a high surface area relative to their volume, are more effective than most of the most modern polymeric-type conventional fertilizers on the market. Its characteristics may also enable sustained release and promote continuous, efficient N uptake by the crops. As a result, this technique offers the biggest foundation for creative and sustainable nutrient transport systems for crops, it will make use nano-porous surfaces of plant parts for supplying nutrient. It is necessary for the modern period to use encapsulated nanoparticles like nano clays and zeolites-based nano nutrients because they enhance fertilizer efficiency, recover depleted soils, revitalize ailing crops, and control pollution [5].

Primary and secondary macronutrient nano fertilizers

According to current developments, nano fertilizers have a significant role in modern agriculture due to the availability of formulations and delivery systems that maximize plant uptake [19]. These fertilizers prevent chemical changes in soil and minimize nutrient losses such as leaching to improve use effectiveness and environmental quality [20]. We are exploring the potential of nanoparticles based on a variety of metals and metal oxides in agricultural applications. Crops really benefit from nano particles, which have various dynamics and are very small in size [21]. Basic nutrients (primary) N, P, and K as well as the secondary nutrients like Ca, Mg and S are delivered to plants in quite substantial amounts over an extended period in macronutrient nano fertilizers. According to projections, by the end of 2050, there will be a 263 MT rise in the need for macronutrient fertilizers globally. Because of their increased surface area and capacity to penetrate, engineered nanoparticles have a greater nutrient utilization efficiency than conventional fertilizers [18]. Furthermore, yield can be increased as a result of the applied nano fertilizers' temporal release pattern, which more effectively increases the N uptake efficiency of treated plants than the fertilizer administered conventionally [22]. Surprisingly, a laboratory study found that gradual N release was associated with a noticeable increase in rice output, even with a 50% reduction in dosage compared to conventional urea [23]. An increase in crop yield was attributed to the synergistic impacts of nanoscale N, Zn, and Cu. The nano N foliar spray improved the leaf's capacity to absorb N, which had a direct impact on the sink (source) (fruit) [24].

The excessive application of traditional macronutrient sources (primary and secondary nutrients) fertilizers to soil endangers the well-being of our agroecosystem since runoff from these sources can contaminate water sources, cause eutrophication, and harm aquatic life. Nano fertilizers can be applied as an alternative to conventional fertilizers and may have a smaller negative impact on the environment overall. Through tailored delivery mechanisms and continuous availability of nutrients in terms of time and space, the advantages of these nano nutrients would be combined with increased crop productivity.

Advantages of nano over other kind of fertilizers

Granular fertilizers are synthesized into nano fertilizers, whose basic materials are obtained by various means from the plant's vegetative and reproductive organs (methods using physical, chemical, biological, and mechanical processes). It was used to boost agricultural productivity in terms of both quantity and quality, and nanoparticles could be made totally from bulk materials [25].

The traditional way of applying nutrients to soil is in the form of granules. Once the nutrients have dissolved in the soil and taken on ionic forms, they can then be absorbed by plant roots both actively and passively. If the active ingredients are present in nanoforms, the effects may differ significantly when the delivery technique is changed. At the nanoscale, the bulk material's physicochemical features are found to be different than those at the smaller size. As previously reported, applying rock phosphate in nano form to soil may increase the availability of P to plants while also preventing nutrient fixation in soil. In addition, because rock phosphate nanoform lacks silicic acid, it depends on Fe and Ca for P fixation, it increases plant P availability [26].

Since nano fertilizers pose less of a threat to the environment than traditional fertilizers, they are increasingly being used. It can improve soil nutrient status, while also increasing crop output and quality. A farmer can cut input costs and increase profit margins in this way. In the interim, it improves efficiency of fertilizers and less damage to environment. Along with increasing productivity, it also increases the nutritional value of crops and their grains and enhances food flavor. When Fe nanoparticles are used to their full potential in wheat crops, the grain's protein content rises. In addition to promoting crop growth by preventing disease, it also increases crop stability by preventing lodging and having a deeper root system [27]. For improving agricultural productivity, application of balanced fertilizer to the crops, this can be done by using nanotechnology. When compared to traditional fertilizers, nano fertilizers increase all morphometric parameters of the plants with increased photosynthate generation and transport to several organs. Nanotechnology's advantages over conventional based fertilizers and improving crop health were mentioned in figure 3, figure 4 and table 1 [28].

Plant absorption and uptake of nanoparticles

Several variables, including the nanoparticle's composition, the plant's physiology, and how nanomaterials interact with the environment, all have an impact on how well plants absorb nanoparticles. The characteristics of the nanoparticle had a substantial impact on its function, and the plant was able to absorb it. The size of nanoparticles appears to be one of the primary obstacles to their uptake into plant tissues. Some reports claim that plants only allow nanoparticles up to 40 to 50 nm in size to move, penetrate, and accumulate inside their cells [8, 29]. Movement of nanoparticles within a plant is crucial because it can reveal accumulation sites and potential entry points for nanomaterials. Nanomaterial uptake from soil and water in conjunction with environment depends on exposure mode and nanoparticle physical/chemical properties [30].

Upon entering a plant, nanoparticles can use one of two routes: the apoplast or the symplast for instance, if nanoparticles are largely carried through the xylem and not the phloem, then nanoparticles may likely flow mostly from root part to shoot parts, leaves, and other sections of the plant, rather than downwards, and thus should be given to the roots to ensure a proper distribution throughout the plant system. However, to obtain uniform dispersion, foliar application should be employed, if the nanoparticles show good translocation via the food conducting tissue/phloem. Additionally, plant organs serving as sinks, including fruits and grains, will probably start to gather nanomaterials that are being moved or transported along the phloem. An essential aspect that must be taken, while attempting to prevent future consumption of nanomaterials by people or animals after spraying foliage. Salt ions may cause precipitation and have a conflicting effect in comparison. In addition, the symbiotic interaction between plants and microorganisms affects plant uptake of nanoparticles [31, 32].

Various elements affect how well nanoparticles are absorbed, taken up, transported, and penetrated by plants.

- How the plant system noticed the nanoparticles and how they translocated within the plant.
- In the soil, nanoparticles have the potential to interact with a variety of microbes and ions, which could either help or hinder how well they are absorbed.

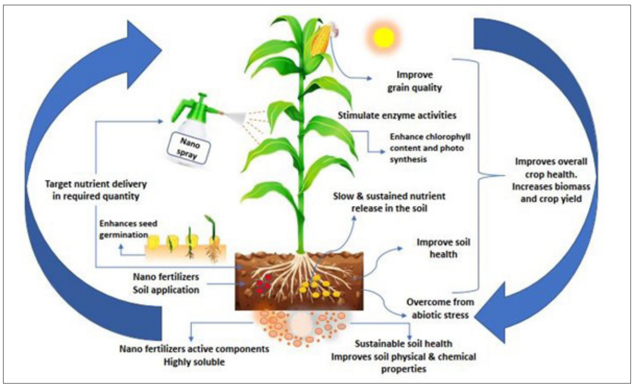

Figure 3: Influence of nano nutrient to improve crop health.

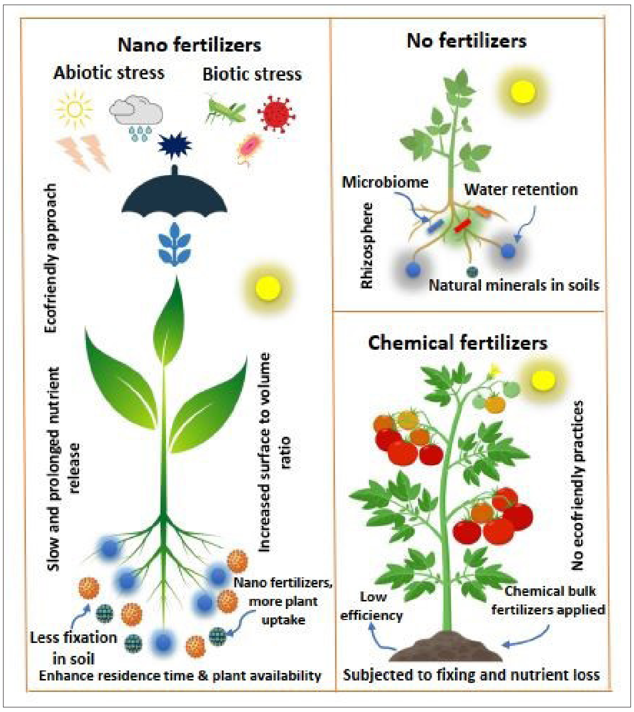

Figure 4: Nano fertilizers comparison to conventional fertilizers.

- Through apoplastic or symplastic channels, nanoparticles can move upwards and downwards in the plant and can even alter their course radially.
- Endocytosis, pore formation (perhaps mediated by carrier proteins), and plasmodesmata are among the proposed mechanisms for internalization.

Several factors, including the nature of the particles, how they interact with nature and plant system, influence how plants respond to nanoparticles. Still Pérez-de-Luque [8] the precise process by which nanoparticles enter root tissue is yet not fully understood. It is commonly acknowledged that "cellular penetration" is crucial to the process of particles absorption during nutrient and water uptake [33, 34]. Plant absorption of nutrients and uptake was shown in figure 5.

Applications of nano fertilizers in improving yield and quality

Nano fertilizer has potential to raise the quality of various products, there has been a rise in interest, how ideas from nan-

Table 1: Applications of nano fertilizer-based technologies over conventional based technology fertilizers.

Dissolution and distribution of trace minerals	Increased bioavailability and decreased soil absorption and fixation may result from using a nano-sized formulation of mineral micronutrients.	Large particle size, reduced solubility; a problem for trace mineral dissolution and dispersion.
Nutrient uptake efficiency	Fertiliser efficiency and nutrient uptake ratio in crop production could be improved with the use of a nanostructured formulation, which could also reduce fertiliser waste.	Roots have less access to resources due to the lack of bulk composite.
Controlled release	Encapsulation in envelope forms of semipermeable membranes coated by resin-polymer waxes and sulphur may allow for fine control over the release rate and release pattern of nutrients for water-soluble fertilisers.	The natural equilibrium of soil could be upset if too many fertilisers are applied as once.
Effective duration of nutrient release	Fertilisers with a nanostructured formulation can have a greater impact on soil health for a longer period of time.	When nutrients are delivered to plants, they take what they need, and the excess is transformed into insoluble salts by the soil.
Loss rate of fertilizer nutrients	Fertiliser nutrient loss can be decreased by using a nanostructured formulation. Fertiliser nutrient loss can be decreased by using a nanostructured formulation.	Significant amounts are lost due to leaching, rain, and drift.

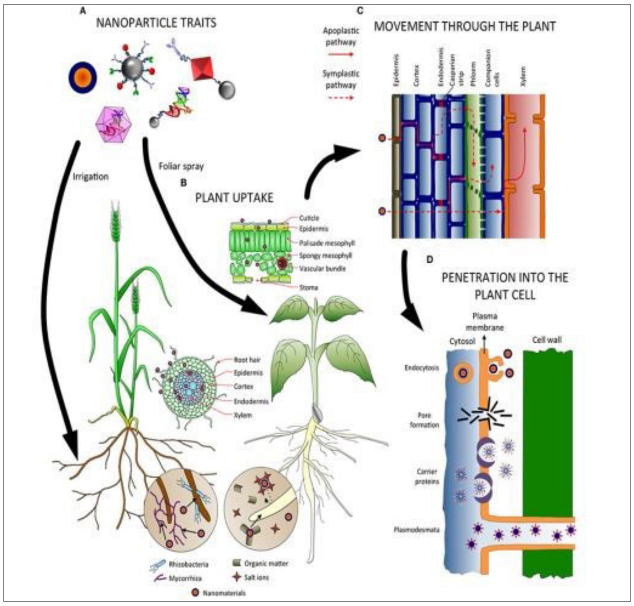

Figure 5: Plant absorption and uptake of nanoparticles [8].

otechnology may be applied to farming and the food supply in countries like India. One of the most common direct uses of nanotechnology is the delivery of different agrochemicals [35]. Different nano fertilizer dosages applied foliar to wheat plants at various stages could significantly improve all yield metrics (spike length, grain per spike) [36] and the seed yield of many crops is significantly impacted by using nano products, nano Fe+ nano Zn nutrient applied in foliar form produced 34 per cent more seed yield. Similar results like 23 per cent seed yield improvement observed by application of macro nutrients in nano form (NPK) and Zn and Fe [37]. Application Zn in the form of oxidized Zn in nano form resulted in higher yield with improving all growth and yield related parameters [38] and also observed that application of P in nano form, it will increase the use efficiency of P, in turn it has contributed to higher growth and yield of maize [39].

Nano fertilizer is a new innovation that significantly increases agriculture production. It was shown in one experiment that foliar treatment of 640 mg ha^{-1} nano P generated 80 kg P per hectare equivalent yield of cluster bean and pearl millet in a dry environment [40]. Therefore, it is crucial to utilize nanotechnology to boost crop yield while reducing nutrient losses through bulk fertilizer application. Some characteristics of nano fertilizers or nano-encapsulated nutrients make them useful to crops, such as regulated chemical release and the release of nutrients on demand for larger duration in soil [41]. Many papers have discussed the benefits of nanoparticle micronutrients for plant growth, which have been studied extensively. Researchers found that spraying pumpkin plants with manganese oxide nanoparticles resulted in optimal vegetative and morphometric growth, as well as high fruit and production quality [42]. The usage of nano fertilizers has a greater influence on increasing cotton production yield in addition to cutting fertilizer prices and greatly reducing environmental concerns.

Nano fertilizer foliar application significantly boosted seed cotton yield, boll weight, boll open rate, and total boll count compared to bulk fertilizer application to soil [43]. Application nutrients through foliar mode, Zn, Fe, N, P and K nanoparticles which boost chickpea yield components [37]. Foliar nano N application increased fruit yield by 17% to 44% and fruit production per tree by 15% to 38% [44]. Spraying grapevines with 0.4 ppm nano Zn increased leaf area, fresh weight, and dry weight, total carbohydrate, Fe content in the leaf, cluster number, cluster weight, and overall yield all increased dramatically after the vine was treated with 1.2 ppm nano Zn [45]. The results of the study also demonstrated that, in comparison to conventional fertilizer, the application of nano Zn at concentrations of 0.4, 0.8, 1 ppm, and 1.2 ppm considerably enhanced yield [46]. Seedlings treated with nanoparticles (NPs) have more pigments that absorb light (chlorophylls and carotenoids). Due to increased carotenoid deposition in the leaves of seedlings treated with NPs, the non-photochemical quenching (NPQ) of PSII was enhanced. Silica nanoparticles ($nSiO_2$) outperformed the other NPs and can be used alone or with others to alleviate chilling stress on sugarcane crops.

Applying 500 ppm of nano ZnS (zinc sulfide) by foliar spray at 55 days post-sowing significantly increased sunflower seed yield. Nano ZnO (zinc oxide) has been shown to be more effective in boosting productivity and absorbing Zn particles than its bulkier counterpart because of its high surface area to volume ratio [47]. Several nano particle fertilizers have beneficial effects of improving yield and quality, so there is a scope of taking this application technique to larger farming community.

Antimicrobial peptides' potential in agriculture: for food security

Agricultural production, particularly the management of diseases, can be enhanced using AMPs. One of the biggest threats to food security is biotic stress, which is brought on by organisms like pests and diseases. In food-deficit regions with rapidly expanding populations, biotic stress can reduce agricultural yields by as much as 40 percent [48]. Current climate change can make this situation much worse by raising the likelihood of microbial infection and foliar herbivory [49]. To ensure that people across the world have access to nutritious food, scientists have been working to create disease and pest resistant crop varieties. Exogenous application of AMPs and transgenic expression of AMP-producing genes are two methods for increasing plant resistance to diseases [50]. Although AMPs have strong action and are easily metabolized without diminishing food quality, they are not widely used in agriculture due to a number of factors. These include their expensive manufacture, potential toxicity, poor stability during transport, and simple hydrolysis by proteases [32]. In addition, AMPs are a greener and safer option for pest and disease management. Several research improved the tolerance of rice, wheat, potato, tomato, banana, and soybean to biotic and abiotic stress by creating transgenic plants producing AMPs. In conclusion, this research shows that expressing AMPs has great promise for boosting resistance to pests, pathogens, and abiotic stress.

Figure 6 shows a few examples of how NanoAMPs have been used in agriculture. One such example is P-13@AgNPs, which was created by combining an antimicrobial peptide (P-13) with silver nanoparticles (AgNPs). This combination improves the NanoAMP's activity against both Gram-negative and Gram-positive bacteria [51].

Soil health improvement by application of nano nutrient elements

The characteristic behavior of nanoparticles in soils is still

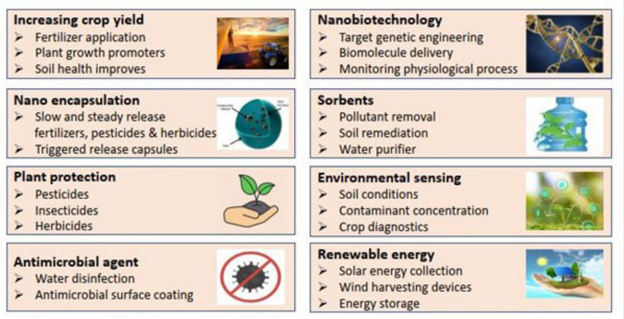

Figure 6: Potential applications of carbon-based nanomaterials in environmental and agricultural sectors.

obscure level. Advanced techniques and equipment's are to be developed to conduct studies of the reactions that occur at the or in the nano-pores within soil matrices. Due to the variety of agricultural applications for nanotechnology, NPs may infiltrate the environment through a variety of channels due to their nature and features. There are numerous sources of NPs in the environment, including both point and diffuse releases [40].

In the last 50 years, India's usage of fertilizers has grown rapidly, from 0.5 MT in the 1960s to 24 MT in 2013, which is equivalent to a four-fold increase in the output of food grains (254 million tons). The majority of these non-renewable fertilizer supplies are depleting at an alarmingly rapid rate, which is a concern for the long-term stability of sustainable agriculture. Understanding that the applied fertilizers only utilize 20 - 50% of the N, 10 - 25% of the P, and 40 - 60% of the potassium is agonizing [35]. Spraying or incorporating nano formulations of micronutrients into the soil can enhance soil health and vigor and increase crop output.

When compared to chemical traditional fertilizers, these nano fertilizers are more advantageous since they?

- Boost nutrient utilization efficiency by three times.
- Chemical fertilizers are 80 - 100 times less necessary.
- Crops are 10 times more tolerant of stress.
- Physiologically, the plants mobilize 30% more nutrients.
- 17 - 54 percent increase in crop productivity.
- An improvement in soil structure, moisture retention, and carbon buildup, in comparison to traditional fertilizers [35].

Nanotechnology has several uses in soil:

- Nano zeolites, which improve soil structure and conserve soil while releasing fertilizers gradually.
- Nano-magnets can be used to remove soil pollutants.
- Plants and bacteria are exposed to more enzymes.
- Nanoparticles to increase soil microorganisms, release of polysaccharides for improved soil structure, moisture retention, and carbon accumulation [40].

Nano carbon's effects on soil erosion and nutrient loss were examined using artificial simulation of rain in the plots.

In the semi-arid loess region of northwest China, specifically in the sandy soil on the Loess Plateau, with 0.7% nano carbon (NC) addition (36.47 kg/h m^2 on a mass basis), the percolation of soil water was significantly reduced and improved run-off water from soil, loss of nutrients from soil was reduced to a greater extent. As a result, nano carbon may have enormous promise for controlling soil erosion on China's Loess Plateau [52]. Figure 7 shows some of the new techniques/applications in agriculture to improve efficiency of applied nutrients.

In a nutshell, customers tend to be skeptical of new technologies, therefore it is important to explain what nanotechnology is, what it entails, and how it is used in agriculture. As researchers, it is our duty to spread the word about this novel technique to a broad audience of growers. To that we can use outreach and high-profile popular science [8].

Conclusion

The potential of nanotechnology applications in agriculture to enhance environmental conditions is considerable since it offers the ability to reduce nutrient losses and enhance agricultural plant productivity and quality. In this review, we have synthesized the latest scholarly investigations pertaining to the utilization of nanotechnology in enhancing crop productivity. The application of nanotechnology in the field of agriculture is now in its nascent phase. Nano fertilizers have emerged as a highly promising and sustainable solution within the agricultural industry, presenting themselves as the optimal choice for implementing an effective farming plan. The increased utilization of nano fertilizers in agricultural practices has the potential to enhance crop productivity while simultaneously mitigating the financial burden and environmental impact associated with traditional fertilizers. Nano fertilizers have enhanced solubility and reactivity, hence facilitating improved cuticle penetration of nutrients, controlled release mechanisms, and targeted distribution. Nano fertilizers have been observed to mitigate abiotic stress, alleviate heavy metal toxicity, and enhance crop growth, yield, quality, and nitrogen use efficiency (NUE). The field of nanotechnology in agriculture is experiencing significant growth. Numerous research endeavors are currently underway to explore potential uses in the field of pesticide, bio-pesticide, and fertilizer delivery. The investigation of nano nutrient delivery within plant systems encompasses the examination of the impact of nano fertilizers on both soil composition and soil-beneficial microorganisms. Additionally, it is imperative to explore the destiny of nano fertilizers in both soil and plants, as well as to assess the optimal concentration and application rates. Consequently, a comprehensive analysis of these factors is necessary to understand the potential effects of nano fertilizers.

Acknowledgements

None.

Conflict of Interest

None.

References

1. Alshaal T, El-Ramady H. 2017. Foliar application: from plant nutrition to biofortification. *Env Biodivers Soil Secur* 1: 71-83. https://doi.org/10.21608/jenvbs.2017.1089.1006
2. Elemike EE, Uzoh IM, Onwudiwe DC, Babalola OO. 2019. The role of nanotechnology in the fortification of plant nutrients and improvement of crop production. *Appl Sci* 9(3): 499. https://doi.org/10.3390/app9030499
3. Usman M, Farooq M, Wakeel A, Nawaz A, Cheema SA, et al. 2020. Nanotechnology in agriculture: current status, challenges and future opportunities. *Sci Total Environ* 721: 137778. https://doi.org/10.1016/j.scitotenv.2020.137778
4. Raliya R, Saharan V, Dimkpa C, Biswas P. 2018. Nanofertilizer for precision and sustainable agriculture: current state and future perspectives. *J Agric Food Chem* 66(26): 6487-6503. https://doi.org/10.1021/acs.jafc.7b02178
5. Manjunatha SB, Biradar D, Aladakatti Y. 2016. Nanotechnology and its applications in agriculture: a review. *J Farm Sci* 29(1): 1-13.
6. Grün AL, Emmerling C. 2018. Long-term effects of environmentally relevant concentrations of silver nanoparticles on major soil bacterial phyla of a loamy soil. *Environ Sci Eur* 30(1): 31. https://doi.org/10.1186/s12302-018-0160-2
7. Schwab F, Zhai G, Kern M, Turner A, Schnoor JL, et al. 2016. Barriers, pathways and processes for uptake, translocation and accumulation of nanomaterials in plants – critical review. *Nanotoxicology* 10(3): 257-278. https://doi.org/10.3109/17435390.2015.1048326
8. Pérez-de-Luque A. 2017. Interaction of nanomaterials with plants: what do we need for real applications in agriculture. *Front Environ Sci* 5: 12. https://doi.org/10.3389/fenvs.2017.00012
9. Adhikari, Tapan, Biswas AK, Kundu S. 2010. Nanofertilizer- a new simension in agriculture. *Indian J Fert* 6: 22-24.
10. Qureshi A, Singh DK, Dwivedi S. 2018. Nano-fertilizers: a novel way for enhancing nutrient use efficiency and crop productivity. *Int J Curr Microbiol App Sci* **7**(2): 3325-3335. https://doi.org/10.20546/ijcmas.2018.702.398
11. Nieves-Cordones M, Ródenas R, Lara A, Martínez V, Rubio F. 2019. The combination of K+ deficiency with other environmental stresses: what is the outcome? *Physiol Plant* 165(2): 264-276. https://doi.org/10.1111/ppl.12827
12. Sharma M, Nath K, Sharma RK, Kumar CJ, Chaudhary A. 2022. Ensemble averaging of transfer learning models for identification of nutritional deficiency in rice plant. *Electronics* 11(1): 148. https://doi.org/10.3390/electronics11010148
13. Ishaq O, Adisaa, Venkata L, Reddy P, Jose R, et al. 2019. Recent advances in nano-enabled fertilizers and pesticides: A critical review of mechanisms of action. *Environ Sci Nano* 6: 2002-2030. https://doi.org/10.1039/C9EN00265K
14. Subramanian KS, Manikandan A, Thirunavukkarasu M, Rahale CS. 2015. Nano-fertilizers for balanced crop nutrition. In Rai M, Ribeiro C, Mattoso L, Duran N (eds) Nanotechnologies in Food and Agriculture. Springer International Publishing, Cham, pp 69-80.
15. Yin J, Wang Y, Gilbertson LM. 2018. Opportunities to advance sustainable design of nano-enabled agriculture identified through a literature review. *Environ Sci Nano* 5: 11-26. https://doi.org/10.1039/C7EN00766C
16. Mahender A, Swamy BPM, Anandan A, Ali J. 2019. Tolerance of iron-deficient and - toxic soil conditions in rice. *Plants* 8(2): 31. https://doi.org/10.3390/plants8020031
17. Singh MD. 2017. Nano-fertilizers is a new way to increase nutrients use efficiency in crop production. Int *J Agri Sci* 9(7) 3831-3833.
18. Chhipa H. 2017. Nanofertilizers and nanopesticides for agriculture. *Environ Chem Lett* 15(1): 15-22. https://doi.org/10.1007/s10311-016-0600-4

19. Mittal D, Kaur G, Singh P, Yadav K, Ali SA. 2020. Nanoparticle-based sustainable agriculture and food science: recent advances and future outlook. *Front Nanotechnol* 2: 579954. https://doi.org/10.3389/fnano.2020.579954
20. Saharan V, Kumaraswamy RV, Choudhary RC, Kumari S, Pal A, et al. 2016. Cu-chitosan nanoparticle mediated sustainable approach to enhance seedling growth in maize by mobilizing reserved food. *J Agric Food Chem* 64(31): 6148-6155. https://doi.org/10.1021/acs.jafc.6b02239
21. Chugh G, Siddique K, Solaiman Z. 2021. Nanobiotechnology for agriculture: smart technology for combating nutrient deficiencies with nanotoxicity challenges. *Sustainability* 13(4): 1781. https://doi.org/10.3390/su13041781
22. Kottegoda N, Munaweera I, Madusanka N, Karunaratne V. 2011. A green slow-release fertilizer composition based on urea-modified hydroxyapatite nanoparticles encapsulated wood. *Cur Sci* 101(1): 73-78.
23. Kottegoda N, Sandaruwan C, Priyadarshana G, Siriwardhana A, Rathnayake UA, et al. 2017. Urea-hydroxyapatite nanohybrids for slow release of nitrogen. *ACS Nano* 11(2): 1214-1221. https://doi.org/10.1021/acsnano.6b07781
24. Ruban JS, Gayathri B, Jeyaraj C. 2021. Bioefficacy of nano nutrients (N, Zn & Cu) on yield of capsicum. *Plant Archives* 21(2): 386-390. https://doi.org/10.51470/PLANTARCHIVES.2021.v21.no2.060
25. Hediat MH, Salama. 2012. Effects of silver nanoparticles in some crop plants, Common bean (*Phaseolus vulgaris* L.) and corn (*Zea mays* L.). *International Research Journal of Biotechnology* 3(10): 190-197.
26. Joseph T, Kralova K. 2015. Application of nanotechnology in agriculture and food industry, its prospects and risks. *Ecol Chem Eng* 22(3): 321-361.
27. Tarafdar JC, Raliya R, Tathore I. 2012. Microbial synthesis of phosphorous nanoparticle from tri-calcium phosphate using *Aspergillus tubingensis* TFR-5. *J Bionanosci* 6(2): 84-89. https://doi.org/10.1166/jbns.2012.1077
28. Cui HX, Sun CJ, Liu Q, Jiang J, Gu W. 2010. Applications of nanotechnology in agrochemical formulation, perspectives, challenges and strategies. International Conference on Nanoagri, Sao Pedro, Brazil, June 20-25.
29. Taylor AF, Rylott EL, Anderson CW, Bruce NC. 2014. Investigating the toxicity, uptake, nanoparticle formation and genetic response of plants to gold. *PLoS One* 9(4): 93793. https://doi.org/10.1371%2Fjournal.pone.0093793
30. Rico CM, Majumdar S, Duarte-Gardea M, Peralta-Videa JR, Gardea--Torresdey JL. 2011. Interaction of nanoparticles with edible plants and their possible implications in the food chain. *J Agric Food Chem* 59(8): 3485-3498. https://doi.org/10.1021%2Fjf104517j
31. Feng Y, Cui X, He S, Dong G, Chen M, et al. 2013. The role of metal nanoparticles in influencing arbuscular mycorrhizal fungi effects on plant growth. *Environ Sci Technol* 47(16): 9496-9504. https://doi.org/10.1021/es402109n
32. Wang F, Liu X, Shi Z, Tong R, Adams CA, et al. 2016. *Arbuscular mycorrhizae* alleviate negative effects of zinc oxide nanoparticle and zinc accumulation in maize plants-a soil microcosm experiment. *Chemosphere* 147: 88-97. https://doi.org/10.1016/j.chemosphere.2015.12.076
33. Asli S, Neumann M. 2009. Colloidal suspensions of clay or titanium dioxide nanoparticles can inhibit leaf growth and transpiration via physical effects on root water transport. *Plant Cell Environ* 32(5): 577-584. https://doi.org/10.1111/j.1365-3040.2009.01952.x
34. Mukherjee A, Peralta-Videa JR, Gardea-Torresdey J, White JC. 2016. Effects and Uptake of Nanoparticles in Plants. In: Xing B, Vecitis CD, Senesi N (eds) Engineered Nanoparticles and the Environment: Biophysicochemical Processes and Toxicity: Biophysicochemical Processes and Toxicity, Wiley, pp 386-408.
35. Veeresh H, Raghavendra M, Singh YV, Sharma SK, Hanamant MH, et al. 2020. Application of nano technology in crop production to enhance resource use efficiency with special reference to soil and water conservation: a review. *J Soil Water Conserv* 19(4): 375-381. http://doi.org/10.5958/2455-7145.2020.00050.8
36. Abdel-Aziz HMM, Hasaneen MN, Aya MO. 2018. Foliar application of nano chitosan NPK fertilizer improves the yield of wheat plants grown on two different soils. *Egypt J Exp Biol* 14(1): 63-72. http://doi.org/10.5455/egyjebb.20180106032701
37. Drostkar E, Talebi R, Kanouni H. 2016. Foliar application of Fe, Zn and NPK nano-fertilizers on seed yield and morphological traits in chickpea under rainfed condition. *J Res Ecol* 4(2): 221-228.
38. Hussein MM, Abou-Baker NH. 2018. The contribution of nano-zinc to alleviate salinity stress on cotton plants. *Royal Soc Open Sci* 5(8): 171809. https://doi.org/10.1098/rsos.171809
39. Rashmi CM, Prakash SS. 2023. Effect of nano phosphorus fertilizers on growth and yield of maize (*Zea mays* L.) in central dry zone of Karnataka. *Mysore J Agric Sci* 57(2): 286-293.
40. Tarafdar JC, Tapan Adhikari. 2016. Nanotechnology in Soil Science and Plant Nutrition. In Adhikari T, Kundu S, Rao AS (eds) New India Publishing Agency, pp 27-33.
41. De Rosa M, Monreal C, Schnitzer M, Walsh R, Sultan Y. 2010. Nanotechnology in fertilizers. *Nat Nanotechnol* 5(2): 91. https://doi.org/10.1038/nnano.2010.2
42. Ahmed S, Hassan AA, Dina M, Salama ME, El-Aziz, et al. 2019. Green synthesis of nanofertilizers and their application as a foliar for *Cucurbita pepo* L. *J Nanomaterials* 2019: 3476347. https://doi.org/10.1155/2019/3476347
43. Sohair EED, Abdall AA, Amany AM, Faruque HMD, Houda RA. 2018. Evaluation of nitrogen, phosphorus and potassium nano-fertilizers on yield, yield components and fiber properties of egyptian cotton (*Gossyppium Barbadense* L.). *J Plant Sci Crop Prot* 1(3): 302.
44. Sohrab D, Ali T, Gholamhossein DSD. 2017. Effects of foliar nano-nitrogen and urea fertilizers on the physical and chemical properties of pomegranate (*Punica granatum* cv. Ardestani) fruits. *Hort Sci* 52(2): 288-294. https://doi.org/10.21273/HORTSCI11248-16
45. Rasha El-Said EE, Saeed AEE, Ahmed AEME, Essam AES, Mohamed MSS. 2019. Efficiency of nano-zinc foliar spray on growth, yield and fruit quality of flame seedless grape. *J Appl Sci* 19: 612-617. https://doi.org/10.3923/jas.2019.612.617
46. Nabil EI, Sunoja VSJ, Wena Y, Zhua JJ, Muralidharana G, et al. 2020. Foliar application of nanoparticles mitigates the chilling effect on photosynthesis and photoprotection in sugarcane. *Plant Physio Biochem* 149: 50-60. https://doi.org/10.1016/j.plaphy.2020.01.035
47. Khanm H, Vaishnavi BA, Shankar AG. 2018. Raise of nano-fertilizer era: effect of nano scale zinc oxide particles on the germination, growth and yield of tomato (*Solanum lycopersicum*). *Int J Curr Microbiol App Sci* 7(5): 1861-1871. https://doi.org/10.20546/ijcmas.2018.705.219
48. Savary S, Willocquet L, Pethybridge SJ, Esker P, McRoberts N, et al. 2019. The global burden of pathogens and pests on major food crops. *Nat Ecol Evol* 3(3): 430-439. https://doi.org/10.1038/s41559-018-0793-y
49. Chaloner TM, Gurr SJ, Bebber DP. 2021. Plant pathogen infection risk tracks global crop yields under climate change. *Nat Clim Chang* 11(8): 710-715. https://doi.org/10.1038/s41558-021-01104-8
50. Li J, Hu S, Jian W, Xie C, Yang X. 2021. Plant antimicrobial peptides: structures, functions, and applications. *Bot Stud* 62(1): 5. https://doi.org/10.1186/s40529-021-00312-x
51. Gao J, Na H, Zhong R, Yuan M, Guo J, et al. 2020. One step synthesis of antimicrobial peptide protected silver nanoparticles: the core-shell mutual enhancement of antibacterial activity. *Colloids Surf B Biointerfaces* 186: 110704. https://doi.org/10.1016/j.colsurfb.2019.110704
52. Beibei Z, Chen X, Wang Q, Wei W, Zhang T. 2018. Effects of nano carbon on soil erosion and nutrient loss in a semi-arid loess region of north western China. *Int J Agric Biol Eng* 11(1): 138-145.