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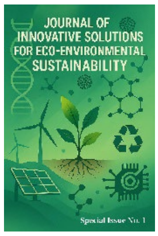

Review Article

Emerging Role of Nanotechnology in Biofortification, Plant Growth, and Crop Protection: A Comprehensive Review

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ABSTRACT

Global climate change and rapid population growth pose challenges to food security and also require crop improvement techniques to improve the quality and quantity of crops. To ensure food security, advanced nanotechnology and nano-engineering are tools to increase crop yields and ensure sustainability in the face of climate change, where the agricultural world is facing many unprecedented challenges. and reduce losses to achieve production. Nano-particles and nano-materials provide a wide scope for fertilizers and pesticides. Nano-materials are also creating specialized products for agrochemicals, simplifying and controlling delivery and improving crop protection. Due to the current and considered use of nanotechnology in the management and control products (fertilizers, pesticides, etc.), in this review we list recent information on the new use of nanotechnology in agriculture that will help to meet food and agricultural needs as well as ensures environment security. Although nanotechnologies contribute to the development of the world in many ways, they also face some limitations. Although nanotechnology is at the forefront of modern scientific progress, its negative effects cannot be ignored.

1. Introduction

Nanotechnology in agriculture is a science dealing with all the processes occurring at the molecular level and nanometer length scales. It is manipulation or self-assembly of atoms, molecules or groups of molecules into structures to create materials with new or different properties [1]. Agriculture has been the backbone of most developed countries. It not only feeds us, but also encourages trade. According to the 2022–23 census, the population of India is equivalent to 17.76 per cent of the total world population. Considering this type of food, new technologies that can provide more production in a short time are needed. Accordingly, other factors affecting agriculture include the deficiency of macro and micro nutrients, refugees, trade, water depletion, soil and soil erosion. It may be one of the places where all these shortcomings can be overcome in a smarter way than nanotechnology. Since the main problem is fertilizer, nanofertilizer production will be a new technology in this field. Fertilizers can be sprayed on the soil, foliage, and even the aquatic environment in many ways; nanofertilizer increases the effective utilization of nutrients by 3 times and also increases stress. Nanotechnology is the collection of atomic information including physical, catalytic, magnetic and optical properties at the nanoscale [2]. Nanotechnology has now emerged as an interdisciplinary field and is frequently used in other branches of science such as physics, electronics, engineering and in the biomedicine and pharmaceutical industries, thus successfully improving the delivery of traditional medicine [3]. Recent advances in nanotechnology are affecting many sectors, including biomedical applications, manufacturing, telecommunications, renewable energy, and agriculture [4]. Increased government and private sector funding in nanoscience R&D is a result of the new field of nanotechnology. Its size in at least one dimension is between 1 and 100 nm and falls into the category of nanotechnology. Nanoparticles can improve the performance of plants and bacteria and make the utilization of nutrients more efficient due to their high surface area, strong reactivity and better penetration into cells [5]. Metal sulfide

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nanoparticles have recently been recognized as non-toxic materials with promising applications such as high-energy batteries, chalcogenide glasses and precursors for electronic devices, electronic products and solar products [6]. Size, structure and properties are the three characteristics of each engineered nanoparticle. Many industries including materials, transportation, pharmaceutical, cosmetics, agriculture and many more industries have been developed with the help of nanoparticles [7].

2. Properties of Metal Nanoparticles

Nanoparticles exhibit unique optical and magnetic properties due to small size differences [8]. Metal nanoparticles have attracted great attention in many scientific and industrial applications due to their unique properties based on quantum size effects and large surface area to volume ratio. Nanoparticles are sometimes unstable when dissolved in solution and must therefore be stabilized with the help of some stabilizing agents that provide electrical or steric protection to prevent their aggregation and association, such as water-soluble polymers, quaternary ammonium salts, surfactants or polyoxyanions. Together, they eventually lead to the formation of lumpy metal.

3. Magnetic Properties

Sulphides of iron have different magnetic properties depending on the iron and sulphur ratio [9]. Magnetic property of any nanoparticle can be altered by its surface free energy which also decides its reactivity. Supermagnetism is a phenomenon or unique form of magnetism exhibited by nanoparticles that are made of a ferro- or ferromagnetic material and having size below a certain range, generally 10–20 nm [8].

4. Photophysical and Photochemical Properties

The optical, electrical, and chemical properties exhibited by thin metal nanoclusters in the nanometer range have potential applications in optoelectronic nanodevices and biological nanosensors. In recent years, many studies have begun in the field of synthesis and organic functionalization of metal nanoparticles of different shapes and sizes. Optical and electrical properties of metal nanoparticles play a role in light-emitting reactions, and noble metal nanoparticles exhibit better electrical properties due to their electrical properties and size-volume difference [10].

5. Surface Plasmon Resonance Properties

As first reported by Mie [11], the interaction of metal nanoparticles with light occurs in the non-electrical coupling of the metal and nanoparticle lattice in resonance with the light field. This phenomenon is called surface plasmon resonance (SPR). Due to plasmon resonance, the effectiveness of metal nanoparticles is increased, thus improving the use of metal nanoparticles in biological diseases [12].

6. Importance of Nanoparticles

A lot of research has been done in the field of nanotechnology and it has been used in many products such as textiles, sunscreen, cosmetics and toys, as well as drug delivery, biosensors and biomedical applications. Nanotechnology is also being developed for use in the environment, such as pollution control [13]. An important aspect of nanotechnology in agriculture is nanofertilizers, which should be obtained from plants at a very low cost and harmlessly. Heat therapy is a treatment using heat. In the ancient cultures of Egypt, India, and China, diseases such as smallpox, skin diseases, syphilis, and measles were treated with gold [14, 15]. Gold is used in many medical devices, including heart rate monitors, gold implants in the middle ear, and gold-plated stents used to treat heart disease. Silver nanoparticles (AgNPs) can be used to treat life-threatening diseases such as cancer, lung disease, HIV, and many other antiviral drugs. They are also used in drug delivery, cancer, and tumor hyperthermia. Additionally, AgNPs have anti-inflammatory properties and can delay tumor growth [16]. Pd-Cu nanoparticles are highly selective, strong and stable catalysts that can hydrogenate CO_2 to C_2H_5OH. The highest turnover frequency was observed after optimizing the Pd/Cu ratio [17]. The metals silver and copper are often used as additives in a variety of applications, such as antifouling paints, antimicrobial textiles, and wood preservation. With recent advances in material science, the use of metals has expanded to metal surfaces and coatings, chelates, and nanomaterials. Metal nanoparticles are valued for their ability to be incorporated into polymer matrices and their improved conductivity compared to traditional materials. Currently, metal nanoparticles have emerged as an ideal delivery vehicle for biosensors and drugs. Various metals have been investigated for the synthesis of metal nanoparticles. Gold and silver nanoparticles are very important in the biomedical field because they can be easily surface functionalized and the discovery of various ligands such as peptides, sugars, proteins and DNA for surface decoration [3]. There are many applications of metal nanoparticles in industry. However, the diversity of nanoparticles in the environment makes them toxic to organisms, and toxicity depends on size, morphology, composition, surface area, etc [18].

7. Sources and Environmental Behavior of Nanoparticles

Nanoparticles are abundant in nature because they are produced by many natural processes, including volcanic eruptions, forest fires, photochemical reactions, easy erosion, and production by plants and animals [19]. The use and production of nanoparticles result in the release of engineered or manufactured nanoparticles into the atmosphere. These products have attracted a lot of attention and are associated with the atmosphere in which they are presented. The reactive behavior and effects of nanoparticles in air by colloidal species (1–1000 nm) and naturally occurring nanoparticles (1–100 nm) have been investigated for many years [20]. According to the source, nanomaterials can be divided into three main groups: (iii) Natural nanomaterials, which can be obtained in insects, plants, microorganisms, animals and humans. (ii) Incidental nanomaterials are industry-produced nanomaterials, such as nanoparticles produced from welding fumes, combustion processes, car engine exhaust, and even some other natural causes such as forest fires; Products required for a specific application. However, the differences between the three sources of nanoparticles are often unclear. Sometimes the nature of nanomaterials is considered as a group of nanomaterials. One of the key differences in the production of nanomaterials is that the size and shape of nanomaterials can often be better controlled than traditional nanomaterials. Emerging and naturally occurring nanomaterials are constantly being created and dispersed on the surface, soil, ocean, soil, and air [21]. To understand the role and behavior of nanoparticles in water, it is necessary to understand their interactions with natural waters such as environmental colloids and organic matter under various physicochemical conditions (such as cation concentration type and pH value). These interactions are controlled by different processes such as formation in the natural organic matter (NOM) layer on the nanoparticle surface, aggregation, decomposition, and interactions with micropollutants. In general, the interaction of bacteria with nanoparticles depends on the composition, size, structure, morphology and porosity of the nanoparticles [22]. However, there are reports that nanomaterials used in equipment remain in surface water [23,24]. Experimental data [25] indicate that mg L^{-1} nanoparticles can be found in surface water and may vary depending on the amount used and the increase of advance. has been launched.

8. Biofortification of Crops with Tthe Help of Nanotechnology

The absorption of water forms the prerequisite in confirming that biofortification in crops lead to improved micronutrient content. However, constant monitoring might be necessary on its consumption over a prolonged period of time [26]. Henceforth, clinical trials are essential to evaluate the impact of micronutrient status and related outcomes (e.g. vision tests related to vitamin-A enriched crops, assessments of physical performance for iron-rich plants, etc.). Several studies have proven the effectiveness of beans and pearl millet, biofortified with iron in enhancing the target population's nutrient status. Iron deficient population of school candidates in Rwanda after consuming iron biofortified beans for about 4.5 months, demonstrated an increased heme levels resulting in improved total iron in body [27]. A similar impact was observed with the effectiveness of pearl millet among the students aged between 15–17 years in Maharashtra, India. The consumption of iron- enriched biofortified pearl millet flatbread daily for four consecutive months led to improvements in serum ferritin and iron status in young adults having iron deficiency. The prevalence of iron deficiency was reduced significantly in the group provided with biofortified pearl millet with high iron content. Among the children diagnosed with iron deficiency (64%), a significant proportion overcame deficiency over a span of six months [28]. In the similar vein, biofortified zeolite, when consumed as a grain serves as a dietary source of vitamin A. in an effective study conducted on Zambian children aged 5–7 years depicted that compared to control group, the children in the orange maize group had higher stores of vitamin A in their bodies after three months [29].

9. Need for Biofortification

Consuming biofortified staple crops will improve human health and nutrition. Biofortification holds comparatively two major advantages: Firstly, cost effective benefits and secondly, it has the potential to reach rural communities that are underserved. Globally, a greater population suffers from micronutrient deficiency (about one-third population) [30]. These deficiencies occur gradually with irregular intake and improper absorption of minerals and vitamins to sustain proper health and development. Steady and significant rise in the costs of non-food product has further reduced access good food for the lower strata of the society [31]. The inclusion of biofortified food crops in daily diet can alleviate the nutritional deficiencies [32]. To assess and incorporate the nutritional benefits, the researchers must analyse the nutritional quantities retained post cooking, processing, packaging and storage, ensuring the sufficient quantities in food for the consumers [26]. Unfortunately, staple food crops lack sufficient levels of micronutrients essential for human growth.

10. Methods for Biofortification

The essential micronutrients can be incorporated for biofortification of the crops using three basic methods: genetic modification methods, traditional methods and, accordingly, agronomic methods including the use of biotechnology, crop cultivation and fertilization strategies. Crops targeted by genetic modification, cultivation and agriculture include staple crops such as rice, wheat, corn, sorghum, lupine, beans, potatoes, sweet potatoes and tomatoes. Cassava, cauliflower and bananas have been biofortified through genetic modification and breeding, while barley, soybeans, lettuce, carrots, rapeseed and mustard have been biofortified through genetic modification and agricultural methods. The number of crops targeted by genetic modification is high and the use of biofortification through breeding is also high. All three methods focus on grains as the main crops. The same goes for beans and vegetables. Interestingly, biofortification of oilseeds is achieved through genetic modification, as the target is limited to genetic diversity and rarity and there is a linkage between crops. Biofortification of crops and specialty products can be achieved through breeding if a valid form of genetic differentiation is also present at the primary, secondary or secondary level of the crop. In the absence of genetic diversity, genetic modification is a better option. The advantage of transgene-based methods is that once a useful gene is found, it can be used to target multiple products. Some important genes such as phytoene synthase (PSY), carotene desaturase, nicotinamide synthase, and ferritin are used in various situations in various crops [33].

11. Interaction of nanoparticles with Alga, Plant, Mushrooms and Fungi

Organisms such as algae, plants, and fungi are frequently affected by exposure to nanoparticles. The most important control stability and fluidity of colloidal suspension and sedimentation in water systems is the surface of nanoparticles (Figure 1). In order for nanoparticles to interact with algae, causing uptake, growth or poisoning of algae, they must have stable colloid suspensions. Transport of nanoparticles readily binds to soil water, which is ideal for interaction with roots or fungal hyphae.

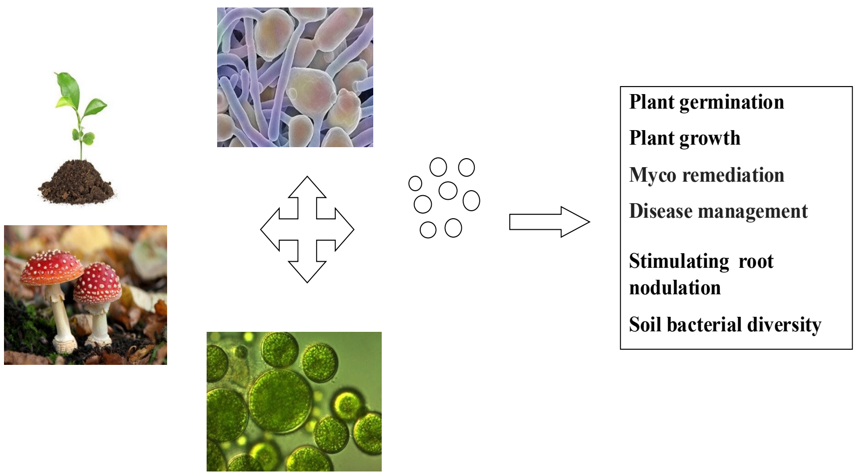

Fig.1. Interaction of nanoparticles with Alga, Plant, Mushrooms and Fungi

The response of algae varies with different chemicals [34]. Gurunathan *et al.* [35] showed that the problematic cyanobacterium Microcystis aeruginosa showed inhibitory effects when treated with silver nanoparticles and that these algae were more sensitive to silver nanoparticles than green algae. Klaine *et al*. [36] reported that the chemical behavior of nanoparticles differs when exposed to seawater and freshwater. Cell walls may be responsible for the toxicity of silver nanoparticles because these nanoparticles have a large surface area/size ratio that enables interaction with cells and connective tissue [37, 38]. It produces free radicals in the body and affects cell function [39]. When nanoparticles enter plants, they can move through tissues through two pathways: apoplast or symplast. The apoplastic movement of granules occurs through the walls of neighboring cells, the plasma membrane, the extracellular space and the xylem vessels, while the symplasmic movement of materials in the cytoplasm of both cells originating from plasmodesmata occurs [40]. Apoplasmic transport factors allow nanomaterials reach vascular tissue and central cylinder making it important for the radial movement in tissues [41, 42]. Once reaching the central cylinder, the xylem acts as a channel through which nanoparticles can move along the flow towards the top of the plant [42, 43]. The movement of some nanomaterials may be restricted in the Casparian band [5, 43, 44]. The movement of products along the phloem tube is another important part of transport that allows distribution to non-photosynthetic tissues and organs [5]. It is possible to apply nanoparticles to the leaf, but in this case the nanomaterials must pass the cuticle barrier in the leaf in a lipophilic or hydrophilic manner. The hydrophilic method arises from polar water pores located in the cuticle or stomata, and the lipophilic method involves the diffusion of products through the cuticle wax [45, 46]. The diameter of the stratum corneum pores is about 2 nm [45], so the best way to penetrate the nanoparticles is through the stratum corneum, which has a size limit supply of more than 10 nm. Descendants of nanotechnology are at the intersection of nanotechnology and biology. Nanoparticles coated with chemical or biological moieties have generated interest in the field of nanodrug delivery systems that have specific and local applications without harming peripheral parts of the body. A few fungi (spore-bearing mushroom bodies) are also used for this purpose, such as *Volvariella volvacea* [47]. Amongst the nanoparticles, the most extensively studied nanoparticles are the ones derived from noble metals namely Ag, Au, Pt, and Pd where, Ag (Silver) holds a significant role in medicine and biology [47]. Nanopaticle biosynthesis plays a crucial role in nanotechnological researches. Various fungi (spore-bearing fungal fruiting bodies) such as *Pleurotus florida*, *Pleurotus volvulus*, *Pleurotus floridis* and *Ganoderma lucidum* have been employed for the relative production of silver nanoparticles [47, 48]. Aloe vera, neem, guava and *Verticillium* wilt*, Kojima flavus*, *Fusarium oxysporum*, *Rhizopus* creeper and the *Penicillium* (endophytic fungus) have been explored for the production of silver nanoparticles [49].

Nanoparticles trigger plant response. Engineered nanoparticles can penetrate plants and leaves and serve as carriers to deliver DNA and drugs to plants [50]; This provides many opportunities for plant biotechnology for genetic engineering and is expressed in plant cells. The ability of plants to capture more light energy by inserting carbon nanotubes into chloroplasts [51, 52], where the carbon nanotubes act as antennas to help chloroplasts detect wavelengths of light that are not in the normal range, such as ultraviolet, green, and near infrared rays. It is indicated that ENPs have positive and negative effects on plant growth and development, mainly depending on the composition, size, and concentration of ENPs, physical and chemical individuals, and plant species [4]. Khodakovskaya *et al.* [53] also showed that the effectiveness of nanoparticles depends on the concentration of use and varies from plant to plant.

12. Effect of nanoparticles on growth of plants

Tripathi *et al.* [71] showed that fresh produce, dry weight, leaf area, fresh leaf area and leaf dry matter increased by 32%, 29%, 44%, 32% and 20% compared to wheat (*Triticum aestivum*) control results respectively when treated with silicon nanoparticles (SiNp). In black mustard medium, application of ZnO NPs was found to have a stimulating effect on shoot growth but inhibited root length. In the environment where 500 mg/L ZnO was applied, shoot length increased by 64% compared to the control, but the same application caused a 61% decrease in root length. Application of nano fertilizer increased yield and have better economics. Foliar application of nano-fertilizers leads to significant improvement of crop productivity of wheat [72]. In fact, treatment with CeO_2-NPs can promote plant growth under certain conditions. It was also found that the use of 10 mg L^{-1} CeO_2-NP in irrigation water slightly improved the growth and yield of tomato plants. After irrigation with 1000 mg kg^{-1} CeO_2-NPs, the weight and dry weight of Brassica napus roots increased by 20% and 100%, respectively [55].

13. Effect of Nanoparticles on Protein Content of Plants

Tripathi *et al.* [71] showed that application of 10 mM SiNP to wheat (*Triticum aestivum*) caused a 7% to 19% reduction in total protein content compared to the control. Krishnaraj *et al.* [74] treated *Bacopa monnieri* (Linn.) with different concentrations of AgNPs and estimated the protein content of different parts of the plant. Plants treated with AgNPs showed lower protein content compared to plants grown under normal conditions. AgNP-exposed plants had higher protein content in leaves on day 5 of treatment, but decreased on subsequent days; There was a 45–50% decrease in protein content on days 10 and 15 of the injuries, but a 45–50% decrease in protein content on days 20 and 15; On day 30, protein content improved. The protein content in roots and stems was estimated to be low for 20 days, after which the protein content increased. The results of Salama [75] showed that AgNPs had a positive effect on the protein content of maize (*Zea mays*) and beans (*Phaseolus vulgaris*). Treatment with silver nanoparticles at concentrations of 20, 40, and 60 ppm increased the protein content of both experimental products. At a concentration of 60 ppm AgNP, the protein content of beans and corn increased by 30% and 24%, respectively, compared to the control group, but at a concentration of 100 ppm, the content of protein content of beans and corn was reduced. 32% and 18%. Corn is overcontrolled. The increase in protein content of both crops indicates that they are recommended for consumption, while the decrease in protein content indicates the toxicity of AgNPs.

14. Effect on Antioxidant System

It is reported that antioxidant agents (ADS) work to detoxify or neutralize the effects of free radicals that can harm the entire body. Too much oxygen in the body and their metabolic deficiencies ultimately lead to oxidative stress [76]. Tripathi *et al.* [71] showed that SiNP application to wheat (*Triticum aestivum*) plants reduced the effect of all non-enzymatic antioxidants. GNP application in mustard seedlings would consistently increase antioxidant enzyme activity and this increase in antioxidant enzyme activity may be due to the stress applied to mustard seedlings after GNP application, leading to better protection from various effects of H_2O_2 [77]. Various harmless compounds to combat reactive oxygen species. Krishnaraj *et al.* [74] showed that the application of AgNPs on *Bacopa monnieri* (Linn.) led to an increase in the total phenolic content in the plant tissues and the results were reported in leaves and roots.

Table 1.
Role of Nanoparticles in Modulating Plant Physiology and Crop Protection

Nanomaterials	Crop Species	Mode of Application	Doses Applied	Treatment Duration	Responses	References
MWCNTs	Sorghum, Soyabean, Maize	Seed priming	100 µg/mL	24 h	Improved Seed Germination and Seedling Growth	[53]
MWCNTs	Wheat, Maize, Groundnut, Garlic	Seed priming	50 µg/mL	Over night	Rapid Germination with Increased Biomass and Water Absorption Efficiency in Seeds	[54]
ZnO	Coffee	Foliar spray	10 mg/L	45 days	Improved Growth, Biomass Production, and Photosynthetic Efficiency	[55]
ZnO	Wheat	Mixed with growth substrate	20 mg/L	Growth cycle	Increased grain yield and biomass accumulation	[55]
ZnO	Cluster bean	Foliar spray	10 mg/L	6 weeks	Enhanced growth, biomass, and nutrient content	[56]
FeS_2	Chickpea, Spinach, Carrot, Mustard	Seed priming	80–100 µg/mL	12–14 h	Increased germination and crop yield	[57-59]
ZnO	Tobacco	Hydroponics	0.2 µM and 1 µM	21 days	Enhanced growth physiology, metabolite levels, enzymatic activity, and anatomical traits and anatomical properties of plants	[60]
Fe/SiO_2	Groundnut, Maize	As fertilizers	15 mg/kg	3 days	Increased growth and biomass accumulation	[61]
TiO_2	Spinach	Seed priming and foliar application	0.25% suspension	48 h and 35 days	Higher biomass, chlorophyll, nitrogen, and protein content.	[62]
AgNPs	Wheat	Mixed with pot soils	50 mg/L and 75 mg/L	Trifoliate stage	Improved growth and tolerance to heat stress	[63]
Ag NPs	Cowpea	Foliar application	50 mg/L	40 days	Improved growth and heat stress tolerance	[37]
TiO_2 and SiO_2	Rice	Foliar application	20 and 30 mg/L	55 days	Mitigated cadmium toxicity, improved growth, and antioxidant activity	[64]
SiO_2 NPs	Rice	Foliar application	2.5 mM/L	70 days	Alleviated heavy metal toxicity by reducing bio-concentration and translocation	[65]
ZnO, CuO and Ag NPs	Plum	Fruit spray	100 & 1000 µg/mL	4 days	Suppressed grey mold and soil-borne diseases	[66]
Al_2O_3 NPs	Tomato	Foliar application	400 mg/L	20 days	Controlled *Fusarium* root rot	[67]
Ag NPs	Cowpea	Foliar application	50–100 µg/mL	7 Days	No phytotoxicity; inhibited Xanthomonas pathogens in vitro	[68]
CuO	Tomato	Foliar application	150–340 µg/mL	11 days	Controlled late blight disease	[69]
MgO	Tomato	Drenching	7–10 µg/mL	7 Days	Suppressed bacterial wilt disease	[70]

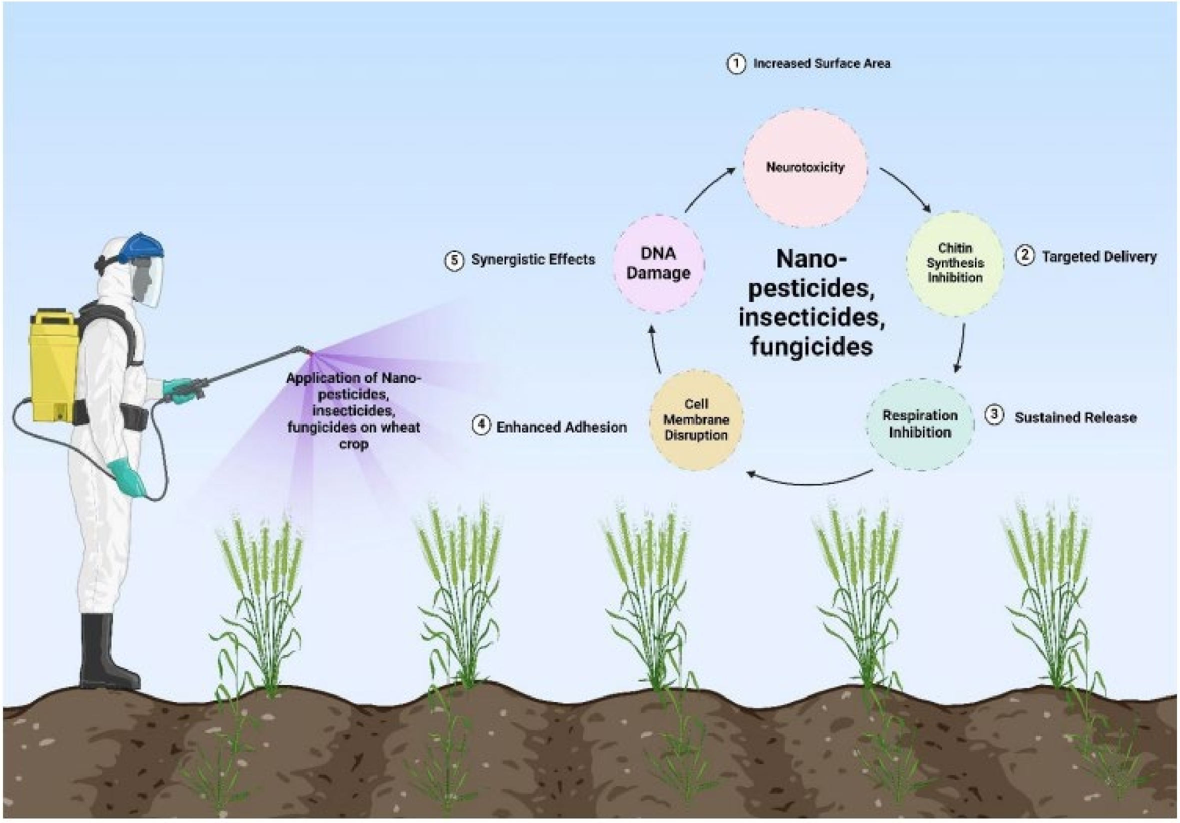

Fig. 2. Nano-enabled pesticides, insecticides, and fungicides: applications and modes of action in crop protection [73]

15. Plant Protection Based Nanomaterials Pesticide

The nanotechnology, in the recent days have experienced an exponential rise in plant protection enhancing its efficacy. In general terms, traditional plant protection involves heavy and excessive use of herbicides and pesticides (Figure 2). Over 90% of the pesticidal usage ends up contaminating the environment due to its failed targeted reactions [78]. Henceforth, it not only raises the production cost but also depletes the ecosystem. To address such critical areas, nano formulations are instrumental in developing innovative formulations of pesticides. The presence of a.i. (active ingredient) in the formulation is effective to target pest control with lowest concentration of pesticide through plant spray. Pesticide nano formulations involve a novel technological intervention of encapsulating the active ingredient for revolutionizing plant protection [79]. The technology of wrapping the a.i. within nanostructures for improving the effectiveness of the pesticides is known as nanoencapsulation [78]. The pesticidal nano formulation can enhance efficacy of pesticides by controlling the potential of the pesticide, which in turn increases crop yield Petosa *et al.* [80]. They found that the nano formulation combined with pyrethroid bifenthrin (nCAP4-BIF) and polymeric nano capsules could timely and reliably produce increased elution rate, even when added to loamy sandy soil initially saturated with Ca^{2+} and Mg^{2+} ions. This suggests that the molecule of nCAP4 might pose a risk carrier for pesticides such as pyrethroids in plant protection. This may be due to the strong dispersibility and wettability ability of the nano formulation, thus reducing organic weight loss and unnecessary pesticides. Additionally, nanomaterials in pesticides show useful properties for a sustainable agri-ecosystem such as hardness, porosity, stability towards heat, increased solubility, crystalline structures and biodegradability [80, 81]. Additionally, permaculture should reduce the use of agricultural chemicals to prevent environmental deterioration and other off-target effects. Additionally, reducing pesticide use can also reduce the cost of crops. The production losses estimated globally from weeds, diseases and pests are worth US$20,000 annually, and in the USA alone the cost of controlling pathogenic organisms amounts to more than US$600 million with the use of fungicides alone [16,41]. Henceforth, in this context the use of nanoparticles has been advocated as an effective method to prevent disease and activity, thereby improving crop heath and production [82]. For instance, halloysite (a clay nanotube) is considered a cost-effective pesticide in agriculture. These nanotubes prolong the active ingredient release time, thus providing better contact and less environmental impact. One such example is nanosilica, which is hydrophobic in nature and can be absorbed by the insect's cuticle upon contact, causing the death of the insect [83]. Great efforts in investigating the importance of nano formulation in controlling AI release has been laid in De Jorge *et al.* [84]. It was observed that the nanofiber structure of pear heartworm (Lepidoptera: Tortricidae) (Busck) pheromones least affected the mortality, suggesting that a.i., pheromone release and long-term insecticides - long-term attraction and lethal effects - were controlled. For example, silica nanosphere formulations can improve the ability of pesticides to penetrate the plant and reach the cellular fluid, thus affecting the digestion or absorption of insects such as aphids [85]. The photodegradation of pesticides can be prevented by devising such hollow formulations [86]. Nano formulation has also been shown to alter the negative behavior of pesticides [87]. When formulated with metal nanoparticles (AuNPs), the negative behavior of ferbam could be changed and absorbed by tea leaves. Such discoveries will elucidate the new way to design pesticides to achieve plant-based resistance to diseases. The gold nanoparticles bioactives synthesized from the latex are known to suppress the trypsin catalytic activity leading to biological control of insect damage. This catalytic inhibition may result from the proteins and metal nanoparticles interaction with through electrostatic interactions, covalent interactions, or -SH groups of amino acids binding [88]. The applications were also found to be infected and infected.

Inorganic nanoparticles such as ZnO, Cu, SiO_2, TiO_2, CaO, MgO, MnO and AgNPs play an important role in various plant defense mechanisms, including microbial and bacterial activity [82,89]. ZnO nanoparticles have recently been used against *Fusarium graminearum*, *Penicillium expansum*, *Alternaria alternata*, *Fusarium oxysporum*, *Rhizopus* creeping, Mucor spp. and has been shown to be effective in controlling the growth of Mucor spp. Flavobacterium and the pathogenic bacterium *Pseudomonas aeruginosa* [82, 90]. Studies have shown that nanocopper application is more effective in controlling Phytophthora infestans than the non-nanocopper formula currently used on tomatoes [69]. Moreover, Si and TiO_2 have been shown to be directly promising in the protection of crop diseases through the activity of pathogens. Likewise, weeds are considered a threat to agriculture worldwide; because weeds compete with crops for nutrients, water and light. However, the use of antibacterial nanomaterials provides an environmentally friendly solution. The photosynthetic pigments of root growth, root and shoot length, fresh and dry weight, and total protein were reduced in plants exposed to SiO_2 nanoparticles [91]. Similarly, the antibiotic (metsulfuron methyl)-loaded pectin, polysaccharide nanoparticles were more cytotoxic to the species of *Chenopodium* both in the laboratory and in the field, and that, comparatively, only small amounts of AI were present compared to commercial herbicides [92]. necessary. In most cases, commercial pesticides control or kill aboveground plants without affecting underground plants such as rhizomes or tubers. Therefore, plants grow again; however, nanoherbicides can prevent plant regrowth [1]. Therefore, the use of nanomaterials in pesticides, fungicides and herbicides has great application possibilities in the sustainable development of agriculture.

16. Potential Risks and Challenges of Nanoparticles

Nano particles alter in their toxicity on the support of their type, length and inception. Their toxicity is further ruled by many different determinants like charge, solubility and binding similarity towards a biological station. Metal NPs and their products are thought-out to be much poisonous accompanying the property of antibacterial, anticandidal, and antifungal ventures. In addition to their fundamental toxicity, NPs also maintain roundabout toxicity generated as a result of their synergy accompanying natural basic compounds [93]. The greatest toxicity maybe the accruing effect of protein corrosion, DNA damage, depletion of respiring chain protons, and production of sensitive oxygen class and inference of apoptosis. The utilization of NPs in agro-environments is often establish expected affecting the PGPR society, accordingly, ultimately moving the plant in addition to soil health [94]. The use of various NPs for the fulfillment of temporary aims, like to reduce bacterium fighting and manure input ability stop in creating a complete question for the farming in addition to controlled community. The unending request of NPs might influence their growth soil structures that can have long term belongings on the society of beneficial microorganisms and fungi [95]. The NPs have existed hidden to plant rhizosphere beneficially uptake of mineral to better their overall output, nevertheless the used NPs maybe threating to the microbiota of the root district that further depends upon any of determinant like, the type of microflora, the makeup of soil and the, natural resources content, delay and dethroning of NPs [96]. The toxicity exercised separately NPs can have various secondary belongings revolving around upon the characteristics of the NPs and the host containers. For instance, the Zinc group of chemical elements NPs of inferior 100 nm made injury to the container obstruction and unfavorably troubled the generative configurations of some gelled waste [96, 97]. In another study administered in *Aspergillus flavus*, the MoO_3 NPs considerably hampered the tumor, convinced the basic contestation, crooked the hyphae form and eventually caused the cessation of cell. Apart from the earlier causes of the container cessation or injury intervened for one NPs to the host containers, the NPs can further hinder the metabolic functioning of the containers, which concede possibility influence irrevocable damage [98]. The synergy of NPs accompanying microorganisms and fungi can further be poisonous and can cause serious damage to the microorganisms developing in their death [99]. The NPs can cause the thorough damage to the cell wall by expending the potential of plasma sheath and can more show reduction of ATP. Additionally, the toxicity shed by the NP and also reduce the bio-functional properties of the bacteria such as biological nitrogen fixation [98].

17. Conclusion

Nanotechnology is arising technique working in all fields of learning. Extensive research is continuing for commercializing nano produce throughout the experience. The function of nanoparticles in farming aims to humble uses of plant protection commodity, underrate nutrient losses and increase yields. The utilization of nano-fertilizers and nano-facilitated delivery methods considerably enhances bio-fortification by improving the uptake, translocation, and utilization of essential micronutrients in plants, through addressing hidden hungriness and undernourishment challenges. Beyond nutrient enrichment, nanoparticles play a vital role in stimulating seed germination, regulating physiological processes, and improving nutrient use efficiency, ultimately promoting sustainable plant growth and higher yields. Equally critical is the improvement of nanotechnology in crop protection, where nano-pesticides, nano-herbicides, and antimicrobial nanoparticles provide effective alternatives to conventional agrochemicals, reducing environmental pollution and ensuring targeted pest and disease management. However, concerns regarding nanotoxicity, bioaccumulation, and ecological safety cannot be overlooked. Standardized protocols, long-term risk assessment, and policy frameworks are essential to ensure safe deployment of nanotechnology in agriculture. Overall, the integration of nanotechnology into bio-fortification, plant growth enhancement, and crop protection strategies represents a promising pathway toward sustainable agriculture and global food security.

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