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Role of nanomaterials in modern agriculture

ABSTRACT

Agriculture is a foundation of several emerging countries, and it is one of the most economically significant drivers. Farmers, consumers, and the environment are all at risk as a result of the increased usage of mineral fertilizers and harmful pesticides. Over the last few years, substantial research into the application of Nanotechnology to boost agricultural productivity has been undertaken. Nanoparticles (NPs) have been discovered to be beneficial as nanopesticides, nanobiosensor, nanofertilizers, and nanoremediation in agrifood production. Nutrients, pesticides, fungicides, and herbicides are compacted with a variety of NPs to facilitate the progressive release of fertilisers and pesticides, resulting in exact dose accessibility to plants. Nanofertilizers improve nutrient utilization, reduce nutrient deficiencies, reduce soil toxicity, and lessen the negative consequences of overdosing, all while reducing treatment frequency. Nanoformulations are used in agriculture to boost germination of seed, reduce nutrient losses in fertilization, reduce the amount of pesticides dispersed, aid water and nutrient management, and. This review also discusses various challenges and concerns about pesticide product development, formulation, and toxicity for ecologically friendly and sustainable agriculture.

Keywords: *Agriculture, nanofertilizers, nanobiosensors, nanopesticides, nanoformulations, nanomaterials*

1. INTRODUCTION

Nanotechnology has gained prominence in recent decades as a technological breakthrough in the food industry. It is a nanometer-scale platform that enables the creation and usage of novel materials by macromolecules, molecules, or atoms with a size of 1–100 nm- [1]. Nanoscience has revolutionized the concept of industrialization, and both the developing and developed nations are keen to invest more in this innovation due to the plethora of opportunities for the creation and application of novel structures, materials, and systems in fields such as agriculture, food, and medicine, among others [2]. Consumers' growing knowledge of the health advantages of food and agricultural goods is pressuring research communities, industry leaders, and farmers to discover a solution to increase food quality without compromising nutritional values.

Currently, nanoscience and its associated technologies are widely regarded as having enormous promise for a wide range of research and applications, including the food and agriculture industries [2]. Agriculture is also optimistic about the long-term viability of this fast-growing technology. Nanotechnology aids agriculture in the production of pesticides and chemical fertilizers by utilizing nanocapsules and nanoparticles (NPs) that have the potential to increase effectiveness, control or delay delivery, absorption, and the production of eco-friendly nanocrystals to enhance the capacity of pesticides for their implementation at lower doses, thereby reducing pollution [3]. Nanotechnology can be used as a broad prospect and covers all major application areas, including, agriculture wastewater treatment, bioremediation of pesticide resistance, nano-biosensors, and nanomaterial production for agriculture, due to its unique features[4, 5]. Less use of chemical fertilizers and pesticides will help in maintaining the natural ecological balance of geo-biological cycles, which has been mess up or disrupted by synthetic chemicals. Researchers are developing agricultural input nano-formulations and encapsulation, which they have tested in vitro and in vivo on a number of

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crops. According to Kuzma et al., 2006 food packaging, animal decontamination and nano-medication, plant defense and fertilizer implementation, genetic manipulation of plants, pollution and restoration of water in the ecosystem, and nano-sensing are all examples of how nanotechnology can be employed in the agri-food business [6]. Insufficiencies in amount of macronutrient and micronutrient, population growth, industrial development, shrinking of water sources, alteration in soil conditions, and erosion of top most soil layer are all factors that affect agriculture, according to this. The fundamental basis for using fertilizer in crop production is to deliver complete micro and macro nutrients that are mostly lacking in soil. Although some fertilizers have a direct impact on plant development, thus accounts for 35-40% of agricultural productivity. To solve all of these shortcomings in a quicker and summary way, nanotechnology can be one of the applications. Given the importance of fertilizers, producing nano-based fertilizers would be a groundbreaking invention in this field [7].

Nanofertilizers boost nutrient usage efficiency (NUE) by three times and help plants deal with stress. Nanotechnology increases biological source utilisation and is environmentally friendly in nature, boosts carbon absorption, and enhances soil aggregation, regardless of the type of crop. Nanotechnology is the study of atoms at the nanoscale level, with an emphasis on their optical, catalytic, magnetic, and physical characteristics [8]. On the other hand, much as biotechnology has a detrimental influence on acquired resistance or gene modification, nanotechnology has a negative imprint on the biological and chemical atmosphere [9]. As a result, before integrating nanotechnology in agricultural techniques, an environmental impact analysis is required. As NUE (nano-fertilizers) increase the nutrient use efficiency three times as well as it also enables plant to tolerate various biotic and abiotic stresses. Nanotechnology can be used on all crop types, it increase the biosource use and also is ecofriendly in nature. It also helps plant in carbon uptake and improves aggregation of soil. As nanotechnology is the science based on nanoscale range, it collects information of atomic particles, with respect to physical, magnetic, optical and catalytic properties [8]. On the other hand, we also know that there are some negative impact of biotechnology like resistance development, manipulation of gene pool, same case is with nanotechnology. It also have some side effects on chemical and biological environment [9]. Thus, it also becomes important to access the environmental impact of nanotechnology before approving it for agricultural practices.

2. FACETS OF NANOTECHNOLOGY IN AGRICULTURE AND FOOD SCIENCE

Nanotechnology is an illustration of a commonly utilised technology with the potential to revolutionise civilisation. Packaging, irrigation, and water filtration, animal feed aquaculture, and other related industries may practically cover every aspect of the agriculture and food sector [10]. Nanotechnology has the potential to transform the agriculture and food industries by offering new techniques and instrumentsfor diagnosis of diseases, targeted treatment, and enhancing plants' capability of nutrient absorbance, fight infections, and withstand environmental stresses, as well as improving plant processing, storage, and packaging [11]. Nanotechnology has given rise to novel customized solutions to problems in plants and food science (post-harvest commodities), as well as novel approaches for rational raw material procurement and processing to enhance crop product quality [12]. Oxygen can cause food to decay and discolour, which is a problem in food packaging and hence was resolved with the development of new nonmaterial for the food packaging. In order to develop these polymers, nanoparticles are used in a zigzag pattern which displayed novel characteristics by acting as a barrier that stops oxygen from entering. Fruit has recently been coated with nano-coatings that completely cover it and prevent it from losing weight or shrinking in size [13]. With the usage of different novel mediators such as nano-sensors, nanoparticles, nano-pesticides, nano-fertilizers, and antimicrobial agentsthe fast spread of nanotechnology has accelerated the changes of traditional food and agriculture systems.The food industry has taken an interest in nanomaterial-based components since many of them include critical nutrients while being non-toxic. Furthermore, the nanoparticles are found to withstand pressure and temperature extremes [2].Nanotechnology has been suggested as having a positive impact on food science and nutrition by increasing the shelf-life of eatables, assisting in the tracking and tracing of contaminants, developing improved food storage strategies, and developing value-added health supplements or antimicrobial agents into food. Nanotechnology could make a significant contribution to food science and agriculture by employing a variety of unique processes and materials such as nanofibers nanomaterials, nanoencapsulation, nanoemulsions, and carbon nanotubes [14].

3. NANOMATERIALS

Nanoparticles are one to one hundred nanometers in size (10^{-9} m). Each particle throughout this scale exhibits different mechanical, optical, and electrical properties as compared to substantial matter, which makes sense given the increased surface area per unit weight or volume in the nano form. Nanoparticles have a privilege over bulk counterparts because of their Surface Plasma Resonance (SPR), Surface Enhanced Raman Scattering (SERS), and Enhanced Rayleigh Scattering (ERS) attributes, which contributes to their development as the foundation for optoelectronics, next-gen electronics, biochemical, and chemical sensors [15, 16]. As a result, nanomaterials have successfully established themselves as among the most intriguing microscopic materials with enormous implications in engineering, medicine, food, and agriculture. A variety of nanomaterials have been suggested for application in agriculture to greatly lower pesticide usage through smart delivery systems, eliminate nutrient deficiencies, and boost productivity through better water and nutrient management [17]. Nonmaterial which can be amorphous or crystalline can function as transporters for gases or liquid droplets. These nanoparticles should be considered a different state of matter from solid, gaseous, liquid, and plasma states due to their quantum size outcomes and large surface area [18]. Several types of nonmaterial are now in use, including crystalline nonmaterial (fullerenes and carbon nanotubes) [19].

4. NANOEMULSION

Nanoemulsions are heterogeneous particulate complexes with oil-in-water emulsion properties that contain solid spheres with amorphous and lipophilic surfaces and droplet sizes ranging from 10 to 1000 nm [20]. Nanoemulsions provide superior optical clarity, physical stability, and bioavailability as compared to conventional emulsions [21]. Nanotechnology applications have been investigated in the food and agriculture sector to enhance food security around the world, such as providing edible coatings for dairy products, cheese, vegetables, fruits, meat, and fish, or smart packaging of foods, which helps to improve the standard of the food [22]. Nanoemulsions are a new food bioactive delivery technology made up of emulsified water in oil or oil in water droplets ranging in size from 50 to 1000 nanometres. The molecule's centre is made up of either oil or water. Even dispersion and active component diffusion through the surfaces are benefits of tiny droplet size in nanoemulsions. Nanoemulsions further improve bioactive component penetration due to the low surface tension and large surface area of the whole emulsion. Furthermore, the manufacturing of both water in oil or oil in water emulsions necessitates a surfactant concentration of 3–10% [23]. Food-grade nanoemulsions are being used more and more to improve encapsulation, absorbability, digestibility, targeted delivery, and bioavailability of active ingredients. Because of the earlier advantages of nanoemulsions over normal emulsions, their use in the food industry has increased. Stabilizers including emulsifiers, weighing agents, ripening retarders and texture modifiers can improve the kinetic stability of nanoemulsions. To improve and enhance pharmacological effects, food-grade derived nanoemulsions are progressively getting employed to incorporate diverse bioactive constituents such as polyunsaturated fatty acids (PUFAs) and Omega-3 fatty acids [24].

5. NANOENCAPSULATION

With the passage of time and advancements in nanotechnology, food bioactive constituents have been explored in systems ranging from simple food systems to very sophisticated systems dubbed innovative bioactive delivery systems. Several of nanotechnology's fundamental achievements in food science include altering the texture of food products, discovering new flavours and fragrances, controlling the discharge of flavours, enhancing the bioavailability of nutritive value, and encapsulating additives and bioactive food components. Encapsulation was first used in biotechnology to enhance the quality of production processes and to promote the degradation of generating cells and their by-product [25]. Later, encapsulation was used to nanotechnology and was shown to be substantially more effective than conventional encapsulating. Encapsulation is a novel method of entrapping active elements or bioactive components/substances in matrix that allow for the controlled release of their payload under regulated settings and rates. Nutrients are protected from uncontrolled conditions using encapsulation methods until they are released in a controlled way. As a result, nanoencapsulation, also known as nanocapsules, is defined as the encapsulation of active components (solids, liquids, and gases) in nanometre-sized capsules [26]. The distribution of any bioactive material to different bodily regions is influenced by particle size [27].When compared to microencapsulation, nanoencapsulation has the potential to improve the controlled release, precise targeting and bioavailability of bioactive substances [28]. Particle size, surface area, shape, size distribution, encapsulation efficiency, solubility, andas well as release mechanisms, have all been documented to be affected by the encapsulation technique and delivery system. As a result, selecting the appropriate encapsulation method based on the required size, physicochemical properties, core material type, and wall material is becoming increasingly crucial. Nanoencapsulation techniques are also more difficult to master than microencapsulation techniques. The major reasons for this include the difficulties in establishing a complex morphology of the capsule and core material, as well as the needs of nanoencapsulate release rates [29].

6. NANOPARTICLES AS A SMART DELIVERY AGENT

The use of nanoparticles as 'smart' delivery systems is an intriguing use of nanoparticles in the field of life sciences. They have already been proposed as 'magic bullets' in 1906 by Nobel laureate P. Ehrlich [30].Delivery systems are critical in agriculture for pesticide and fertiliser administration, as well as plant improvement via genetic material. Pesticide application techniques must focus on efficacy improvement and spray drift management, whereas fertiliser bioavailability is hindered by soil chelation, over-application, and run-offs. Controlled delivery systems for pesticide and fertiliser application offer a feasible solution to these issues. Figure 1 depicts various applications of nanomaterials in the form of nanosensores, nanofertilizers, nanopesticides, nanoherbicides, etc in agriculture for assessing the risk factors and preventing them. The goal of the controlled delivery strategy is to release essential and sufficient amounts of agrochemicals over time in order to achieve maximum biological efficacy while minimising negative consequences [31].In a species-independent method, gene transfer via bombardment of DNA-absorbed gold particles has proved successful in producing transgenic plants [32]. Torney et al. (2007) discovered that silica nanoparticles internalised in plant cells may efficiently transfer DNA and chemicals without the use of specialised equipment [33]. To do this efficiently, it is necessary to conduct research on how transport and penetration operate within the entire plant, its tissues, and cells. The purpose of this study is to develop and apply microscopy tools and techniques with a range of resolutions that are readily available in most research institutes in order to visualise and track the transport and deposition of magnetic nanoparticles inside plants, as well as to explore the potential of concentrating magnetic nanoparticles into specific areas of plants using small magnets. For this reason, sub-micronic and micronic particles were studied as pesticide delivery vehicles. Due to its larger surface area, easy adhesion, and rapid mass transfer, nanoparticles (1000 nm) have the advantage of effective loading over micronic particles (1000 nm). The slow release features of the nanomaterial, the bonding of the chemicals to the material, and the ambient circumstances all contribute to controlled release of the active ingredient. When it comes to genetic material, delivery mechanisms confront obstacles such as restricted cell membrane transit, host range, and nucleus trafficking. Nonetheless, the use of NPs to assist in the transmission of genetic information in order to generate insect-resistant crops is being researched. For example, DNA-coated gold nanoparticles are used as bullets in a device called a 'gene gun' to assault plant tissues and cells in order to induce gene transfer [34].

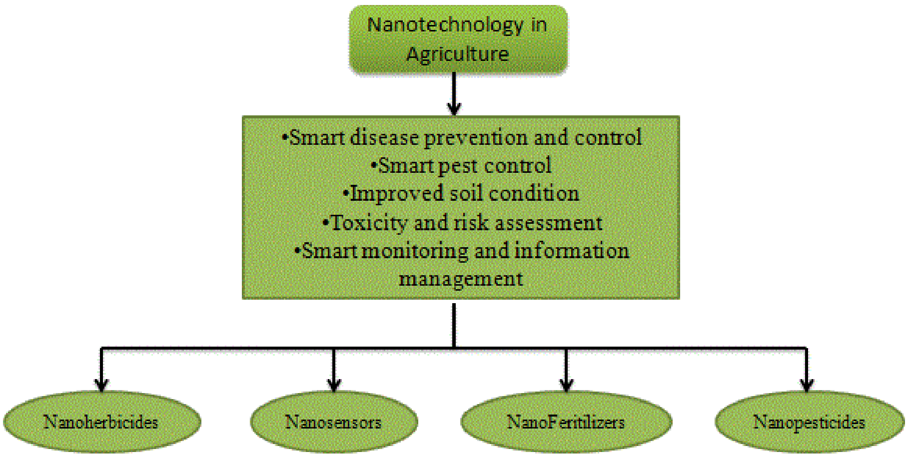

Figure 1. Applications of nanomaterials in the form of nanosensores, nanofertilizers, nanopesticides, nanoherbicides, etc in agriculture for assessing the risk factors and preventing them

7. NANOSENSORS

Nanotechnology-based sensing has exploded in popularity, with a wide range of applications in the food and agriculture industries. Nano-technology enables real-time monitoring of crop progress and farm status, including soil fertility, moisture content, crop nutrition capacity, temperature, plant diseases and pathogens [35]. Nanosensors are emerging as feasible agricultural and food production technology. They significantly outperform conventional chemical and biological approaches in terms of selectivity, speed, and sensitivity. Nanosensors may be used to assess the presence of pollutants, microbes, and the freshness of food. Nanosensors are made up of tiny particles such as carbon nanotubes (high surface area), nanoscale wires (high detection sensitivity), nanoparticles, polymer nanomaterials and thin films.These sensors determine a swap in conductance when a semiconducting carbon nanotube is revealed to specific chemicals. In this current study, we are exploring the applicability and significance of nanosensors in agricultural production and crop management. [35]. Nanosensors, with their chemical and electrooptical capabilities, can help to mitigate the drawbacks of food packaging. Gases, smells, chemical pollutants, viruses, and even changes in ambient conditions can all be detected by nanosensors. Food safety is enhanced by the use of nanosensors, which guarantee that customers receive fresh and appealing foods and help prevent the spread of food-borne diseases. Nanosensors provide a number of benefits over conventional sensors, notably near real-time detection and high sensitivity and selectivity, low cost and mobility, and other significant characteristics that are enhanced when nanoparticles are incorporated into their design. [36].Smart nanosensors have been constructed that can be connected to a GPS system, enabling real-time surveillance of crop husbandry feasible through the use of separate biosensors [37]. Numerous nanosensors are being designed for a variety of agricultural and food industry purposes, including rapidly identifying hazards in the event of potential food illness and putting nanotracers into packaging to demonstrate the food product's history and standard at any given moment. For occasion, nanosensors embedded in food packaging that ascertain microbe growth and alter colour when a preset threshold is met, and nanosensors used during on-line management system to track storage conditions, can assist avoid food poisoning. [38]. It should be noted that nanosensors are important for sensing as well as reporting real-time information about products from production through distribution to consumers. Nanosensors are distant from being merely a passive information-gathering gadget. Nanosensors dispersed throughout the field can detect the presence of plant viruses as well as the quantity of soil nutrients. They also reduce fertilizer use and pollutants in the environment [39]. They are capable of collecting and evaluating data both from remote and local areas, as well as recording, recording, and reporting on it. Nanosensors may be used to handle critical control points along the distribution chain, from the stage of manufacturing or packaging to the point of consumption. Recent improvements have enabled nanosensors to give superior assurance by detecting germs, toxins, and pollutants across the food production chain and capturing data for automated control functions and documentation [36].

8. NANOFERTILIZERS

Fertilizers have been utilised in agriculture for many years forthe advantage of farmers. Traditional fertilisers are not only costly, but they are also damaging to humans and the environment. Nanotechnology is emerging as a possible option in the form of nanofertilizers for the development of environmentally friendly fertilisers with high nutritional value and soil and environment friendliness [40]. A nanofertilizer is made up of nanoformulations of nutrients that are delivered to plants in a way that allows for prolonged and uniform absorption. Nanofertilizers are divided into three types based on the kind of formulation:1) nanoscale fertiliser, which is traditional fertiliser that has been decreased in size and is usually in the form of nanoparticles; 2) standard fertiliser including a supplement nanomaterial is known as nanoscale additive fertiliser, and 3) Nutrients enclosed by nanofilms or intercalated into nanoscale pores of a host material are referred to as nanoscale coating fertiliser [40]. The classification of nanofertilizers is based on nutritional categorization in this case. As a result, micronutrient (Fe, Mn, Zn, Cu, Mo, and Ni) and macronutrient (N, P, K) nanofertilizers are the two most common forms of nanofertilizers. Chemical (bottom-up), physical (top-down), and biological (biosynthetic) techniques can all be used to make nanomaterials for nanofertilizers. The top-down method focuses on lowering the density of bulk counterparts to well-organized nanoscale assemblies. Top-down is a physical method based on material milling. Two disadvantages of this method are the limited control over the size of nanoparticle and a larger quantity of impurities. The bottom-up method begins with molecular level chemical reactions to make nanoparticles. Due to the fact that this is a scientifically controlled synthetic process, it improves particle size control and removes impurities [41, 42]. In addition to physical and chemical methods, nanoparticles may be made biologically utilising the so-called biosynthetic methodology. There are a variety of natural sources for this function, including plants, fungus, and bacteria. The advantage of this method is that it allows for more precise control of particle toxicity and size [43, 44].

Nanofertilizers should be developed to have all of the required features, such as high solubility, stability, time-controlled release, efficiency, increased targeted action with effective concentration, lower eco-toxicity with a safe, and simple means of administration. The following is the procedure for loading nutrients onto these nanoparticles: (a) Assimilation of nanoparticles, (b) Ligand mediated adherence on nanoparticles, (c) Encapsulation of nanoparticles in polymeric jacket, (d) Nanoparticles entrapment, and (e) Nanoparticles synthesis formed of the nutrient itself [45].

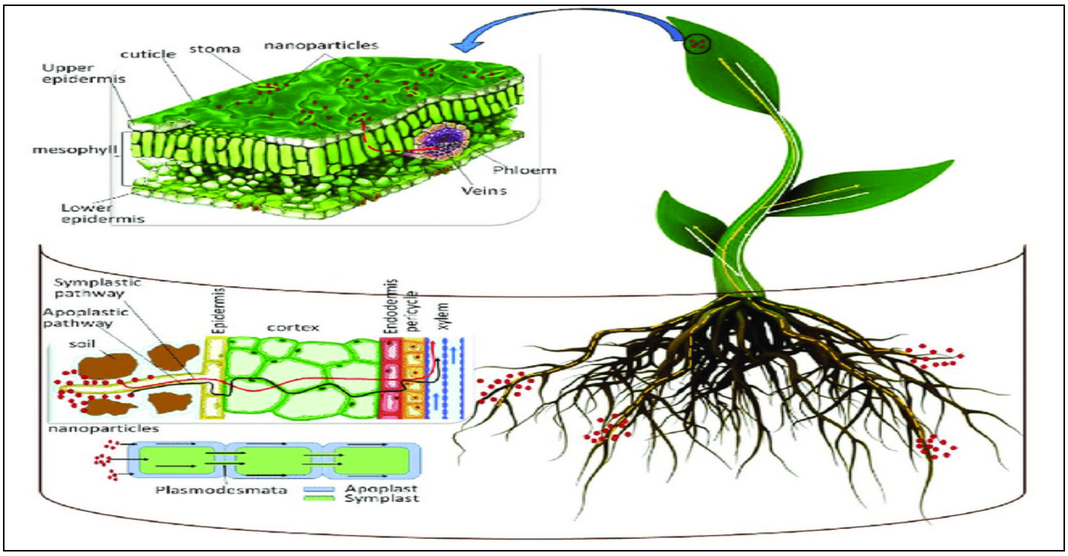

Figure 2. Mechanism of action of nano-fertilizer

Crops can be fertilised with nanoparticles via leaves and roots. NPs have the ability to penetrate endodermis and epidermis of the root, penetrating the xylem vessels and delivering them to aerial portion of the plant. Additionally, NPs can be captured by the stomata of the leaf and transported throughout the plant via the phloem. [46]. NPs must pass through pores in the cell wall that typically range from 3 to 8 nanometers in both cases. As a result, only NPs with a diameter smaller than 8 nm may flow via holes and penetrate the plasma membrane. Absorption and translocation of nanoparticles may vary amongst plants, dependent on the plant's physiology and numerous routes of uptake, transportation, and dispersion [47]. Plants respond to NPs in a number of ways. This emerges to be especially relevant for metal oxide-based nanofertilizers, in which the plant must battle with both the parent nanomaterials and the metal ions produced during the dissolution of customised nanofertilizers [48, 49]. A carrot experiment contrasting the absorbance of metallicoxide nanoparticles (ZnO, CeO_2, or CuO) to that of metal ions indicated because both non-metal oxides and metal ions were absorbed. Such absorption and accumulation in edible portions may not only affect the physiology of plants, but also offer serious health risks to humans [50]. Metallicoxide nanoparticles accumulated on the carrot's outermost surface and did not penetrate the fleshy edible portion, although metallic ions did. Cucumber plants have demonstrated biotransformation in the presence of CeO_2 nanoparticles. The biotransformation reduced Ce (IV) to Ce (III) by 15% and 20% in roots and shoots, respectively [51].

The aggregation of nanoparticles is determined by a variety of parameters, but mostly by the plant species, the tissue/organ utilised straightforwardly as food or for food preparation, and the kind and size of the nanoparticles. Due to the variety in the interactions between NPs and plants, nanoparticles employed in nanofertilizers can aggregate in plants and, in certain situations, create toxicity hazards to both plants and humans. For instance, multi-walled carbon nanotubes cause phytotoxicity in red spinach (*Amaranthus tricolour L.),* inhibiting growth, producing reactive oxygen species, and resulting in cell death [52]. CeO_2 nanoparticles can aggregate and inhibit soybean's ability to fix nitrogen [53]. In chick pea, nanoparticles of zinc oxide boosted germination, root growth, and indole acetic acid production. In Maize, nano-silicon dioxide conferred drought tolerance, increased the number of lateral roots, and increased shoot length. In spinach, nano-TiO_2 boosted vigour indicators and chlorophyll content [54]. In maize, nano-iron slag powder decreased insect pest incidence. In cotton, nano-iron and organic organic fertilizers regulate nutrient release, operate as an effective pesticide, and promote soil fertility. Grapes contain gold nanoparticles and sulphur, which works as an antioxidant. Polyethylene and indium oxide were discovered to promote vegetable photosynthesis. Apart from these, there are a variety of nanofertilizers that offer good characteristics to agriculture from a human welfare standpoint [54].

Nanofertilizers increase the efficiency with which nutrients are used. They improve yield by enhancing plant growth and metabolic processes such as photosynthesis. More nutrient availability aids in the improvement of crop quality parameters such as protein, sugar content,the prevention of biotic and abiotic stress and oil content. Nanofertilizers regulate the rate and dose of encapsulated nutrients and fertilisers to increase crop plant uptake and also reduce fertiliser waste and demand. They increase microbial activity and improve water-holding capacity and soil quality [55].Due to their sensitivity, nanomaterials can combine with many components of their surroundings, resulting in transformation and modification of their physicochemical characteristics. Nanofertilizers can collect in plant sections, inhibiting development, generating reactive oxygen species, and ultimately causing cell death. Due to the reactivity and unpredictability of nanomaterials, safety concerns have been raised for employees who may come into contact with them during their manufacture and use in the field [55].

Table 1. Impact of nanofertilizers on various crop growths

Nanofertilizers					
Nanoparticles	Plant source	Size	Concentration	Impact	Ref.
Aluminium	Ryegrass, Corn, lettuce	1–100 nm	2,000 mg L^{-1}	Decreased root length	[56]
Copper	Lettuce	1–100 nm	0.013% (*w*/*w*)	improved shoot/root ratio	[57]
Copper	Mung bean	1–100 nm	<200 mg L^{-1}	Reduced seedling growth	[58]
Copper	Zucchini	50 nm	1,000 mg L^{-1}	Reduced biomass	[59]
Gold	Cucumber, lettuce	10 nm	62, 100 and 116 mg L^{-1}	Positive effect on germination index	[60]
Iron	Barley, flax, ryegrass	1-100 nm	2,000 and 5,000 mg L^{-1}	Completely inhibited germination	[61]
Silver	Wheat	10 nm	0.5, 1.5, 2.5, 3.5 and 5.0 mg kg^{-1}	Reduced shoot and root length	[62]
Zinc	Corn, cucumber, lettuce, radish, rapeseed, ryegrass		2,000 mg L^{-1}	Reduced root growth and elongation	[56]

9. ROLE OF NANOPARTICLES IN CROP PROTECTION AND PEST MANAGEMENT

Pesticides are valuable for crop protection, disease prevention, food safety, and material safety. However, it is lethal to humans, animals, and non-target organisms. Nanopesticide compositions can improve water solubility, bioavailability, and preserve agrochemicals from deterioration in the environment, revolutionising disease, weed, and pest management in crops [74]. By manipulating the outer layer of the nanocapsules, which releases a small dose over a long period of time and eliminates undesirable pesticide run-off, nanoencapsulation of pesticides is advantageous in controlled and gradual release of active component [37].The size range of nanocapsules and nanoparticles between 0.1 and 1000 nm is critical for plant defence. The nanocapsule's shell contains medicinal substances in its centre. This nanocapsule assists in the entry of agrochemicals into plant tissue, stabilises active ingredients, and releases steadily, gently, or completely once the shell is opened. Shell rupture is reliant on physiological pH changes or enzymatic breakdown and is also dependent on the external environment of nanocapsules [75]. Pesticides embedded in nanoparticles are now being designed with the objective of delivering them on a scheduled basis or in response to an environmental trigger [37].

The use of Ag nanoparticles (AgNPs) as a pesticide-free alternative to suppress sclerotium-forming phytopathogenic fungus was examined. When fungal hyphae were exposed to AgNPs, the sections of the hyphal wall disintegrated and the hyphae collapsed. AgNPs were also tested for their effect on undiscovered fungal species of the genus Raffaelea that cause oak tree mortality, and it was discovered that AgNPs had a detrimental influence on conidial germination [76].

Table 2. Impact of various nanopesticides

Nanoparticles	Size	Concentration	Effective against	Impact	Ref.
Silicon	20–60 nm	1, 1.5, 2, and 2.5 g/kg	*Callosobruchus maculates*	Insects and larvae are killed in a dose-dependent manner. It's good for keeping grain safe while it's being kept.	[63]
Silicon		200, 300, and 400 ppm	*Spodoptera littoralis*	Induces the death of larvae in a dose-dependent manner. After 15 days, the plant's lifetime and number of leaves per plant had increased.	[64]
Silicon	20–30 nm	50, 100, 200, and 300 ppm	*Rhyzopertha dominica, Tribolium confusum*	Insects are killed in a dose and size-dependent manner. The effect of NPs was found to be stronger on wheat grains than on barley grains. It's good for keeping grains safe while they're being stored.	[65]
Silver		0.1 µg/mL	*Xanthomonas campestris pv. Campestris*	Substantial cabbage decrease, black rot in the growth chamber	[66]
Validamycin loaded nano sized calcium carbonate	50–200 nm		*Rhizoctonia solani*	Validamycin nano formulation has a higher germicidal efficacy	[67]
Thiamine di-lauryl sulfate (TDS) nano	(258.6 nm)	100 ppm	*C. gloeosporioides*	The Halfa was destroyed by 80 percent growth suppression of C. gloeosporioides and TDS nano particles	[68]
Chitosan nano particles	20-100 nm		*Rhizopus sp. Colletotrichum capsici, C. gloeosporioides,*	In comparison to the control, mycelia growth is delayed.	[69]
Nano copper		0.2 ppm	*Xanthomonas axonopodis pv. punicae*	Nano copper suppressed development 10,000 times more effectively than the commonly prescribed amount of Cu-oxychloride	[70]
Titanium		≈ 500 to 800 ppm	*Xanthomonas perforans*	Photocatalytic activity that is significantly higher than that of the control and decreased bacterial spot without causing any negative consequences impact on yield.	[71]
Copper nano particles	11–55 nm		*Phytophthora infestans*	At lower doses, it was more effective than commercial agrochemicals	[72]
Silver nano particles	1-100 nm		*Xanthomonas performance*	When compared to untreated tomato transplants, the bacterial spot disease was reduced.	[73]
Titanium with zinc	1-100 nm		Bacteria	When compared to the untreated control and other commercial bactericides, there was a significant reduction in bacterial spot.	[71]

10. NANOPARTICLES MECHANISM OF ACTION

Here we discuss the major mechanisms underlying nanomaterial toxicity, including (1) NPs' effects on ATP production, DNA replication, and gene expression; (2) NPs' generation of reactive oxygen species (ROS); (3) NPs' disruption of the integrity of cell membranes; (4) NPs' disruption of energy transduction; (5) NPs' release of toxic components; and (6) NPs' destabilisation and oxidation of proteins.

11. IMPACT ON ATP PRODUCTION, DNA REPLICATION AND GENE EXPRESSION

At low concentrations, nano ions may interact with enzymes in the respiratory chain, including NADH dehydrogenase, leading to the uncoupling of ATP generation from respiration. Furthermore, the binding of ionic nanoparticles to the transport protein results in proton leakage and the breakdown of the proton motive force [77]. Additional proteomic tests on *Bacillus thuringiensis*-exposed silver nanoparticles demonstrated an influence on the aggregation of envelope protein precursors, suggesting a function for the proton motive force [78]. DNA marking and DNA cleavage are two applications of nanomaterial interactions with nucleic acids. In contrast to the beneficial uses of DNA-nanomaterial conjugation, fullerenes have been discovered to bind DNA and produce strand deformation, thereby impacting the molecule's function and stability. Cross-linking, DNA strand breakage, and sugar or base adducts are all secondary effects of ROS released by certain nanoparticles[79]. Gene polymerization in vivo utilising polymerase chain reaction (PCR) revealed frequent DNA alterations in cells that had taken up nano ions .Sunscreens containing titanium dioxide nanoparticles may cause supercoiled DNA to become nicked due to the presence of oxygen radicals. Cleavage of double-stranded DNA by photosensitive fullerenes is very context-dependent and requires a specific fullerene derivative. Despite these findings, few investigations on nanoparticle genotoxicity using Ames tests or other protocols have been undertaken, and little is known about their mutagenic effect[80]. Nanoparticles and ions may impact DNA replication and gene expression. Silver ions impede DNA replication [79]. Silver nanoparticles attach to E. coli DNA, impairing DNA replication [81].

12. REACTIVE OXYGEN SPECIES (ROS) GENERATION

Distinct kinds of nanoparticles create different forms of ROS by reducing oxygen molecules. Mitochondria produce most ROS from oxidative cellular metabolism. ROS are hydroxyl (OH^-), superoxide (O^{2-}), hydrogen peroxide (H_2O_2), and singlet oxygen ($^1O_2$) [82, 83]. Chemical constitution of designed nanoparticles determines ROS production [84]. ROS are created by nanoparticle absorption and cause cellular oxidative stress, nanotoxicity, DNA damage, cell signalling manipulation, cell motility changes, apoptosis, cytotoxicity, and cancer promotion and initiation [85]. ROS targets DNA. Oxidative DNA damage includes base and sugar lesions, DNA-protein crosslinks, double- and single-strand breaks, and basic sites[86]. ROS play a significant role in some biological processes and in governing cell physiology and function by influencing signal transduction pathways [87]. Normal circumstances balance ROS generation in microbial cells. Cell redox balance promotes oxidation with high ROS production. Unbalanced conditions generate oxidative stress, which destroys microbial cells. Xia et al. (2008) and Yin et al. (2012) found that oxidative stress alters cell membrane permeability and damages microbial cell membranes [82, 88].

13. NANOTECHNOLOGY IN SUSTAINABLE FARMING

The most challenging global issue is ensuring food security for the world's rapidly growing population. According to projections, the world's food demand would climb from 59 to 98 percent by 2050, when the global population will reach 9 billion people [89]. Agriculture supports the majority of the world's population, either directly or indirectly. Chemicals such as insecticides and fertilizers are commonly used to increase food production. Pesticides are employed in agriculture to combat biotic stressors, but they have a detrimental impact on crop quality and soil health. Excessive fertiliser application, such as ammonium salts, nitrate, phosphate compounds, or urea results in a deterioration in soil quality.[90]. Nanotechnology is being widely used in modern agriculture to make precision agriculture a reality. Nanoparticles with one or more dimensions of 100 nm or less are included in nanotechnology[90]. It's an exciting new field of science with plentiful applications in both basic and applied sciences [91]. As a future instrument, nanotechnology may be utilised to repair agricultural divisions; it aids in the discovery of crops' biochemical pathways by displacing conventional methods for studying environmental problems and their implementation to production upgrades [92]. Nanotechnology has led to the development of a wide range of nanomaterials, including nano pesticides, nano insecticides, nanoparticles and nano emulsions. The material used for production of nanomaterials are plant extracts, metal oxides, silicates, ceramics, lipids, emulsions and polymers [93]. The potential use of nanoscale agro - chemicals such as nanoformulations, nanopesticides, nanosensors and nanofertilizers has revolutionised traditional agricultural approaches. Nanotechnology in agriculture can play a vital role to remediate wastewater, improve soil quality and increase crop output using sensors that detect diseases [2, 94]. It is critical to develop cost-effective, high-performing insecticides, pesticides that are environmentally friendly too. Pesticides that are made using concepts like nanotechnology, which could reduce toxicity, improve shelf life, and enhance the solubility of pesticides that are poorly water soluble, all of which could have a good environmental impact [95,96]. There are about 400 companies which are commencing research and development in nanotechnology sector throughout the world, and the number is predicted to rise to more than 1000 in this decade. In the imminent era of agricultural mechanization, new nanotechnology tools and methods can enhance the way agriculture is seen and has a significant future. Precision delivery of fertilizers and nutrients, as well as disease diagnosis at an early stage, have a bright future thanks to biotechnological advancements and the use of nanomaterials to create faster and more precise diagnosis instruments [97].

Nanoparticles possess distinctive interactions within the human body, owing to their diminutive size and heightened responsiveness, which give rise to a range of health issues. Nanoparticles have the ability to trigger oxidative stress by producing reactive oxygen species (ROS), which can result in cellular damage and inflammation [98]. These can have an impact on many organs and systems, potentially leading to the development of diseases such as cancer, cardiovascular ailments, and neurodegenerative disorders. Exposure to specific nanoparticles can induce both acute and chronic inflammation, which can result in tissue damage and contribute to the development of illnesses such as asthma and other respiratory disorders [99]. Nanoparticles have the ability to engage with DNA, resulting in genetic alterations and abnormalities in the structure of chromosomes. The genotoxic effect has the potential to elevate the susceptibility to cancer and other genetic problems. Nanoparticles have the ability to disturb cell membranes, resulting in either cell demise or impairment [100]. This can undermine the structural soundness of different tissues and organs. Nanoparticles can elicit an immunological response as they are perceived as alien entities by the immune system, which can have either beneficial or detrimental effects on the body. This can lead to either hypersensitivity or immunological suppression, which can impact the body's capacity to combat infections and diseases [101]. Certain nanoparticles have the ability to traverse the blood-brain barrier, which could result in neurological consequences and harm to the brain[102]. This gives rise to worries regarding their utilization in medical applications and the possibility of neurotoxicity.

14. CONCLUSION

Innovative tools are now being created that will incorporate nanodevices that will be capable of successfully replacing a variety of various forms of biological equipment. Nanotechnology may enable quick improvements in agricultural research, including reproduction science and technology capable of producing vast amounts of seeds and fruits regardless of the season or period. Nanofertilizers are critical in agriculture for increasing output and resilience to abiotic stressors. Thus, the potential uses of nanofertilizers, nanosensors, and other nanomaterials in agriculture, biotechnology, and horticulture cannot be underestimated. Additionally, nanomaterials were evaluated for their ability to enhance plant height, germination rate, root growth and number of roots, leaf chlorophyll, and antioxidant content of fruits. To attain sustainable crop yields, smart nanofertilizers with the ability to release nutrients according to the plants' temporal and geographical requirements must be developed. In plants, early diagnosis of stress and alleviation of stress effects, as well as disease prevention and treatment are all important.

The entire potential of nanotechnology in the agriculture and food sectors has not yet been realised, although it is rapidly progressing from theoretical knowledge to implementation. To combat viruses, spores, and other crop diseases, agriculture will benefit from smart sensors and smart delivery systems. Before items are commercialised, we must assess the influence of nanotechnology on agriculture. Nanomaterial accumulation and its negative impact on the environment are also key concerns and crucial in the application of nanotechnology. More research is needed to examine the environmental effect of nanomaterials and estimate the non-toxic concentration for each crop.

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Data availability All data generated or analysed during this study are included in this published article and its supplementary information file.

Declarations

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IZVOD

ULOGA NANOMATERIJALA U SAVREMENOJ POLJOPRIVREDI

Poljoprivreda je temelj nekoliko zemalja u usponu i jedan je od ekonomski najznačajnijih pokretača. Poljoprivrednici, potrošači i životna sredina su u opasnosti kao rezultat povećane upotrebe mineralnih đubriva i štetnih pesticida. Tokom poslednjih nekoliko godina, preduzeta su značajna istraživanja o primeni nanotehnologije za povećanje poljoprivredne produktivnosti . Otkriveno je da su nanočestice (NP) korisne kao nanopesticidi, nanobiosenzor, nanođubriva i nanoremedijacija u proizvodnji poljoprivredne hrane. Hranjive materije, pesticidi, fungicidi i herbicidi su sabijeni sa raznim NP -ima kako bi se olakšalo progresivno oslobađanje đubriva i pesticida, što rezultira tačnom dozom dostupnosti biljkama. Nanođubriva poboljšavaju iskorišćenje hranljivih materija, smanjuju nedostatak hranljivih materija, smanjuju toksičnost zemljišta i smanjuju negativne posledice predoziranja, a sve to istovremeno smanjujući učestalost tretmana. Nanoformulacije se koriste u poljoprivredi za povećanje klijanja semena , smanjenje gubitaka hranljivih materija u đubrenju, smanjenje količine raspršenih pesticida, pomoć u upravljanju vodom i hranljivim materijama i . Ovaj pregled takođe razmatra različite izazove i zabrinutosti u vezi sa razvojem proizvoda pesticida , formulacijom i toksičnošću za ekološki prihvatljivu i održivu poljoprivredu.

Ključne reči: *poljoprivreda, nanođubriva, nanobiosenzori, nanopesticidi, nanoformulacije, nanomaterijali.*

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