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MINI-REVIEWS

Era connecting nanotechnology with agricultural sustainability: issues and challenges

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Abstract
The key to promoting good health and livelihood is easy to access sufficient quantities of safe and nutritious food. Modern agriculture faces many obstacles as the population is growing exponentially and the rate of food production is unable to keep up. Additionally, to maintain ecological balance, sustainability must be practiced and damage to the environment should be controlled. As a solution to all these problems, nanotechnology has come forward to produce a variety of nanomaterials that assist in agriculture, i.e., nano-pesticides, nano-fertilizers, nano-emulsions, etc. This review focuses on the union of these two disciplines, which will ensure great advancement. Agri-nanotechnology, a new field is born. It provides a detailed overview of certain widely used and important nanomaterials in modern agriculture while elaborating on their application. Agrochemicals can be improved by nanomaterials in terms of efficacy, accuracy, and specific targeting. Through smart and precision agricultural technologies, it is possible to reduce the amount and improve the efficiency of agrochemicals. Advantages include increased sustainability and cost and time efficiency, whereas disadvantages such as potential toxicity and environmental damage still need to be investigated. Through this review, we hope to truly explore the potential for advancement in agri-nanotechnology with new-age nanomaterials, while discussing the advantages and disadvantages of the same. This is the modern era—an era of connecting technology and agriculture for better output and higher efficiency.

Keywords Nanotechnology · Crop-management · Nano-formulations · Fertilizers · Agriculture-sustainability

Introduction

History and general applications

After the Industrial Revolution and the Green Revolution of the 1960s, nanotechnology established itself as the sixth revolutionary technology. The multidisciplinary approach of nanotechnology has been exploited in various sectors including pharmaceuticals, cosmetics, electronics, and agriculture [26]. In contrast with its use in pharmaceuticals and drug delivery, nanotechnology has only relatively recently been applied to the agriculture and food sectors (Fig. 1). The concept of nanotechnology in agriculture originated approximately half a century ago. The agricultural sector has witnessed tremendous advancement due to the integration of nanotechnology [24].

There is even more potential for advancement in this field as observed by the increasing research in this field and the progressive increase in scientific publication and patents. The scientific fraternity is seeking nanotechnology solutions to various agricultural benefits and environmental challenges due to its robust application [25]. This has contributed to the development and discovery of multiple new avenues in the field of agri-nanotechnology. This innovative approach has contributed greatly to success in various areas such as genetics and plant breeding, waste remediation, nanobioprocessing, detection of plant disease, plant disease management, crop productivity, monitoring of plant growth, increase in global food production, enhancement in food quality and reduction in waste for "sustainable intensification" [63].

Nanotechnology has already benefited agriculture in many different ways. Results include reduced use of agrochemicals due to small delivery system, killing of phytopathogens

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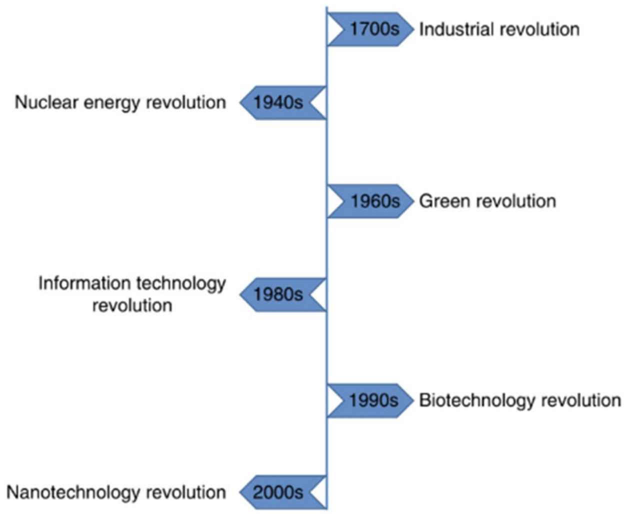

Fig. 1 Evolution of the technology in agriculture section

by nano-pesticides, bio-nanocomposites, use of nano-sensors as smart detecting tools, etc. Nano-fertilizers are also being used to reduce loss and runoff observed while using synthetic fertilizers. The growing trends of publications in different areas of agri-nanotechnology depict the ongoing research and their excellent outcome. The global scenario of research trends in agri-nanotechnology is expected to benefit both society and the agricultural sector enormously [25].

Agricultural nanotechnology

Farming, also known as agriculture, is the process of cultivating plants and raising livestock in order to produce food, feed, fiber, and many other desired products. The agriculture sector is an integral part of the economy of most developing countries and provides direct and indirect food for the human population. Agriculture is the largest and most stable sector of any economy, supplying raw materials to food and feed industries. Agriculture plays a crucial role in the development of an economy by supplying food and enabling people to have a better quality of life [12]. Due to the limited natural resources (production land, water, soil, etc.) and the increasing population, agricultural development needs to be advanced greatly. Agriculture should be developed in an efficient and ecologically responsible manner, in order to manage the scarcity of natural resources (producing land, water, soil, etc.) and to accommodate the growing population [48]. Ecological biodiversity plays an important role in maintaining the delicate balance between the environment and food production as it increases agricultural resistance to environmental stress. Traditional agriculture relies too heavily on non-sustainable and potentially environment-damaging synthetic substances to respond to the rapidly growing demand for food. Up to now, the global use of pesticides and fertilizers has reached 4.1 million tons and 125 million tons, respectively. This traditional way of administering agrochemicals is generally inefficient and must be replaced with more eco-friendly, sufficient, cost-effective, and efficient methodologies.

Newer methods and approaches are always developing to address these important problems. Agricultural and food sciences need to use innovative technologies such as nanotechnology and nano-biotechnology. The application of nanotechnology involves understanding and controlling matter at the nanoscale, where a unique phenomenon provides a platform for new ideas and inventions. It focuses on synthesis, manipulation and functionalization of nanomaterials These approaches have tremendous potential to revolutionize agriculture and allied fields. Nanomaterials are typically understood to be particles having diameters of less than one nanometer (NMs). Due to the high surface-area-to-volume ratio of nanomaterials and their unique physicochemical features, these materials are highly reactive and have the benefit of being easily modified to meet rising demand [39]. This has resulted in a great development of goods based on these technologies. There is a high demand for quick, dependable, and affordable solutions in the twenty-first century for the detection, monitoring and diagnosis of biological host molecules in agricultural sectors. The use of smart nanotools in agricultural systems could revolutionize agricultural methods, decrease or even eliminate the environmental impact of current agriculture and increase both yield quality and yield quantity [63].

Since nanomaterials are so tiny, these are employed in a variety of industries, including agriculture, the biological sciences, aerospace, electronics, and the manufacturing of chemicals. There are several different kinds of nanomaterials used in the agricultural field. Carbon nanotubes are an example of an inorganic nanoparticle used as NM, iron nanoparticles are also often used since their magnetic properties, and silica nanoparticles have drawn attention due to their abundant pore structure and large specific surface area [54]. Copper, gold, or silver nanoparticles have, also, been the subject of other research. Generally, pesticides are transported by organic materials like polymers and liposomes, which are renewable, biodegradable, and eco-friendly. Organic solvents have been replaced by nano-pesticides in their processing and formulation. As an added benefit, they are also more stable against degradation and provide a more efficient release for improved results. Based on the pattern of release, the rate can be divided into two types, i.e., sustained-release and stimulated-release. Nanomaterials are created using biodegradable and eco-friendly materials. Nano-pesticides based on the metal–organic framework (MOF) are particularly interesting. Typical MOFs have inorganic metal centers and organic molecules bound together in a porous framework. As a result of their wide range of physical and chemical properties and extremely high specific surface areas, MOFs are widely used in a variety of applications. Eco-friendly materials are used as key components of their products. Natural and synthetic materials are also used to develop nano-fertilizers. There are three categories of these to match the crop's requirements for release rate and uptake efficiency: (1) Nano-Supported Fertilizers (2) Nano-sized Fertilizers (3) Nano-Wrapped Fertilizers. Fertilizers are required to increase crop yield but they can reduce soil fertility by disturbing the mineral balance in the soil [68]. Additionally, there is a need to regulate the high manufacturing costs of these herbicides and fertilizers. Other NMs come in a variety of forms, including nanoclays, nanotubes, and nanowires, each of which has a specific surface chemical, electrical, and optical characteristics that increase their sensitivity, detection limits, and response times. In addition to these, we also have nano-activity-based growth promotes, nano-emulsions, nano-based delivery systems, nano-biosensors (used in food processing, food quality, food packaging, plant pathogen detection) and so much more. The field grows every day and comes up with new materials and applications.

In order to manage and control matter at the nanoscale (1–100 nm), it is necessary to create new designs for matter, manipulate components and create and apply functioning systems, devices, and materials. At the nanoscale, or at the level of atoms and molecules, nanotechnology makes use of novel processes and properties of matter. It has the potential to address some of the world's most pressing development issues. Many developing nations have adopted nanotechnology programs to improve their capabilities and sustain the pace of economic growth [61]. Nanoscale systems must be assembled using new techniques and equipment. Tiny systems must be combined to create items that are more complicated. In addition to higher performance, nanotechnology goods must be made more affordable [16]. The food and agricultural sectors have paid significant attention to the novel and rising qualities of these new-age materials. With the aid of these cutting-edge materials, modern agriculture is evolving into precision agriculture, in order to extract the most possible from the resources at hand.

The use of NMs in agriculture seeks to minimize production costs, optimize output, decrease product amounts used for plant protection and reduce nutrient losses in order to boost yields [74]. It has the potential to significantly increase the efficiency of agricultural inputs, reduce environmental pollution and reduce labor costs. Without the use of agrochemicals like pesticides, fertilizers, etc., sustainable output and efficiency in contemporary agriculture are unthinkable. However, every agrochemical has certain potential drawbacks, such as water pollution or food product residues that endanger human and environmental health [33]. It is essential that we address the environmental concerns and health risks associated with nano-agrochemicals. It is important to consider the toxicity and environmental safety and impact of these materials. By using nanomaterials, agricultural systems can remain viable and food security can be increased. Agrochemicals based on nanotechnology may eventually have to be associated with other smart technologies to meet the high demands and become as efficient as possible in precision agriculture. NMs might potentially be the future of modern agriculture [56].

Nano-delivery systems

According to Camara, biotic stresses including plant infections, insects, and weeds, as well as abiotic stressors like temperature, floods, drought, and salt, reduce agricultural yield globally by roughly 50%. In order to increase crops' tolerance to various environmental challenges, it is crucial to find novel reactive vectors that can react to environmental cues including temperature, pH, light, redox conditions, and enzymes. There are many different kinds of systems, including systems that react to pH and temperature changes. Natural polymers, particularly silica because of their biodegradability and accessibility, have been used to create "stimulus-controlled delivery systems." The structure of polymers is susceptible to several physio-chemical alterations. The biggest benefit of these reactions is that they are reversible; when the stimulus is removed, the polymers revert to their original structure [34].

The pH of the soil, various plant organs, the physiological processes of the plant, fruit ripening, and the presence of agricultural pests or diseases may all vary in agricultural systems. Thus, the existence of flammable functional groups in the supporting structure, which have charge and create some electrostatic interactions, is necessary for these "nano-system delivery systems" to react to pH changes. The interior portion of the nanoparticles becomes more hydrophobic and less likely to release insecticide because of the high degree of ionization of the alginate polymer at an acidic pH. This interaction with calcium ions also promotes the cross-linking of the polymer network. Electrostatic contacts weaken when the pH increases, enabling water to enter the system and the release of the active ingredient. In general, "pH-sensitive nano-systems" are also heat-sensitive, and at low temperatures, they behave as water-soluble polymers. Camara observed that the polymers separate from the solution when the temperature surpasses the transition point. The lower critical solution temperature (LCST) is the name given to this phase [36]. Using temperature-sensitive nanocarriers constructed of nano-mycetes as shown by Zhang and colleagues optimized the pyrethrin insecticide's release mechanism. To recreate the temperatures during the times when mosquitoes are developing in the water, this discharge was approximated using three temperature settings (13, 18, and 26 ℃). In contrast, at higher temperatures, the release increased with time, reaching 31.9 percent at 18 ℃ and further increasing to 49.7 percent at 26 ℃. At low temperatures, 12 percent of the pyrethrin was released from the implant in the first 16 h and did not alter beyond that time [81].

Biopolymers are ideal for developing environmentally friendly nanoparticles or formulations that react to pH fluctuation because they have desired features including non-toxicity, biocompatibility, and biodegradability. Endogenous elements already existing in the organism function as the triggers for the release of active chemicals. When a reducing agent is present, the disulfide bond's intermammary gap determines how the releasing mechanism works. Therefore, the employment of the nanoparticle-containing thiol groups connected to the gatekeeper via disulfide bonds is required. This regulation only applies to "Redox-responsive nanoparticle systems." E.g., a "responsive redox system" was created for the hormone salicylic acid, a plant growth regulator that controls the defenses of plants in the presence of biotrophic diseases. To effectively manage pests, a variety of enzyme types can be utilized as triggers for the active substances they produce. Particularly vulnerable to enzyme reactions with the biological environment are polymers. Under specific circumstances, these responses are found through signal amplification. The enzymes that phytopathogenic fungi make in the soil that is found in the intestines and salivary glands of insects and their larvae have received particular attention. The release of insecticides in the presence of the enzymes prevalent in insect larvae and larval stages has been the subject of several investigations on enzyme-reactive polymers. For instance, the combination of silicon that has been cross-linked with epichlorohydrin modified carboxymethylcellulose to create microcapsules that contain abamectin benzoate. Cellulase, a digestive enzyme that breaks down the cellulose wall's material into smaller pieces and releases the active component, was present while the release action of the microcapsules was being assessed. After "1 h" of contact with cellulase, approximately 30% of the material was released, and after "30 h," it reached an approximate release of 80%. Less than 20% of the emmamectin is released after "30 h" when the enzymes are not present [21].

Additionally, some systems react to light, such as photosensitive nanoparticles. Different wavelengths of light are absorbed by these nanoparticles that enabling the active molecules produced by light radiation to be controlled in space–time. For instance, Coumarin has researched pesticide release phototriggers. Fipronil and coumarin were the main ingredients in a photo-captured pesticide, and a covalent link between them created an on/off switch. The insecticides released are mostly light-dependent, when exposed to blue light and sunlight, this device effectively controlled the Aedes larvae [73]. Huang, et al. explored in their study that specific importance was given to biocompatible, reactive, biodegradable, and intelligent insecticides with precise controlled release styles capable of responding to microecological environmental variations (heat sensitivity, light sensitivity, humidity, enzymatic action, and soil pH). These prove great benefits as compared to traditional pesticide formulations which have various disadvantages and low efficiency and contribute to severe environmental pollution, such as high organic solvent, dust drift, and poor diffusion [29]. In a previous study, UV light was used as a light source to compare the effects of various micro-encapsulation factors on the light stability of pyraclostrobin in water. The results showed that micro-encapsulation reduced the photolysis rate of insecticides in aquatic environments. It could also effectively improve the thermal and light stability of abamectin benzoate.

Nano-agri formulations

The continual use of artificial fertilizers depletes important, naturally occurring nutrients found in productive soil. Soil acidity is a major contributor to decreased soil fertility. Low soil fertility and nutrient shortage are linked to lower crop yield and low nutrient nutritional value. The food requirement of the world's rising population is increasing at an exponential rate. The indiscriminate use of chemical fertilizers and pesticides causes soil deterioration, environmental (soil, land, and water) pollution, an increase in plant residues, pest and insect resistance, biodiversity loss, harm to human health and the environment, and numerous economic losses (Table 1). Pesticides, for example, contain urea, ammonia, and nitrates, which impair both the environment and human health. Chemical pesticide usage has raised major issues, including environmental degradation, immune system damage, cancer, neurological disorders, metabolic illnesses including diabetes, endocrine disorders, and infertility, in addition to the hazards associated with utilizing chemical fertilizers [72]. Scientists have been looking for substitutes and alternatives because all these problems are related to the usage of pesticides and insecticides (Fig. 2).

Nano-biotechnology-based alternatives that are safe for the environment have been the subject of several research experiments (Fig. 3). Biopesticides are biological chemicals or biological material mixtures that are used to prevent, eliminate, eliminate, control, or alleviate parasites. Plants naturally produce botanical pesticides, commonly referred to as insecticidal plants. The plant world is a rich supply of organic molecules, according to recent scientific studies. An old method of pest management is the use of plants having insecticidal properties. They act as a parasitic defensive mechanism that evolved naturally over millions of

Table 1 The various types of nano-pesticides used in the production of nano-fertilizers, as well as their composition, benefits, and examples of active components

Sr. no	Nanomaterials (NPs)	Concentration/Size	Nano-Pesticides	Pest	Plant blight	Advantages	References
1	Mg-based	0.1, 0.5, 0.7 or 1% (growth media; 50% vermiculite and 50% perlite)	MgONPs	*Ralstonia solanacearum*	Tomato plant resistance to *Ralstonia Solanacearrum*	The incidence of disease was significantly reduced when tomato roots were pre-treated with MgONPs suspension (0.1, 0.5, 0.7, or 1%). Upregulation of salicylic acid-inducible PR1, jasmonic acid-inducible LoxA, ethylene-inducible Osm, and systemic-resistance-related GluA were all part of the mechanism	Imada et al. [31]
	Mg-based	200 or 250 mg/L	MgONPs	*R. solanacearum*	Induced tobacco bacterial wilt	*R. solanacearum*, which caused tobacco bacterial wilt, was effectively suppressed. Physical damage to cell membranes and ROS accumulation were proposed as mechanisms	Imada et al. [31]
	Mg-based	200 or 250 mg/L	Incorporated Mg $(OH)_2$NPs	*X. alfalfa, Psseudomonas Syringae and E. coli*		Within 4 h, it inhibited the growth of *X.alfalfae, pseudomonas syringae*, and *E.coli*. Mg $(OH)_2$NPs had killing activities comparable to kocide 3000, demonstrating their potential as a Cu alternative	Huang et al. [29]

Table 1 (continued)

Sr. no	Nanomaterials (NPs)	Concentration/Size	Nano-Pesticides	Pest	Plant blight	Advantages	References
2	Carbon-based	62.5,125,250 and 500 mg/L	SWCNTs, multiwalled carbon nanotubes (NWCNTs), graphene oxide (GO), reduced graphene oxide (rGO), fullerene(C60)	*Fusarium graminearum* & *Fusarium poae*	C60 inhibited spore germination in *F. graminearum* but not in *F. poae* at 500 mg/L	SWCNTs (500 mg/L) had the strongest antifungal activity, followed by NWC-NTs (500 mg/L), GO (500 mg/L), and rGO (500 mg/L), while AC had no antifungal effect at this tested concentration range. These particles inhibit water uptake while also inducing plasmolysis	Wang et al. [76]
3	Ti-based	500–800 mg/L	TiO_2NPs (Phytochemically active)	*X-perforans*	The pathogen that causes infection in tomato plants	High photocatalytic activity and antibacterial activity to reduce the severity of bacterial spots	Paret et al. [52]
4	Ce based	50 and 250 mg/L by root and foliar path	CeO_2NPs	*Fusarium wilt*	Mediated suppression in tomato	CeO_2NPs at 250 mg/L significantly reduced disease severity by 53% and 57%, respectively	Adisa et al. [1]
5	Mn-based	1 mg/L/40 nm	MnONP	*Fusarium oxysporum f.sp. lycopersici*	Tomato disease	Disease estimates in soil-grown plants were reduced by 28%	Elmer and white [20]

Table 1 (continued)

Sr. no	Nanomaterials (NPs)	Concentration/Size	Nano-Pesticides	Pest	Plant blight	Advantages	References
6	Cu based	1000 mg/L	Cu $(OH)_2$NPs (Kocide 3000)	*Escherichia coli* and *Bacillus subtilis* as well as the plant fungal pathogens, *F.oxysporum, C. lunata, A. alternata* and *P.destructiva*		CuNPs outperformed the traditional fungicide Bavistin (devistin, carbendazim 50% WP) in terms of antibacterial efficiency	Yoon et al. [79]
	Cu based	10 mg/L	$Cu_3(PO_4)_2.3H_2O$ nanosheets	*Fusarium oxysporum f.sp. niveum*	Watermelon (*Citrullus lanatus*) root fungal disease can be prevented	58% decrease in disease progression	Borgatta et al. [8]
	Cu based	10 mg/L	CuONPs	*S.littoralis*	Bt. transgenic cotton and conventional cotton insecticidal activity	Exogenous genes encoding Bt toxin were increased in cotton plant tissue	Ayoub et al. [6]
	Cu based	CuONPs had an LC 50 of 129 mg/L after 11 days of treatment, whereas CaONPs had an LC 50 of 232 mg/L after 3 days	CuNPs	*S.littoralis*	Bt. transgenic cotton and conventional cotton insecticidal activity	CuNPs exhibited faster entomotoxic effects than CaONPs	Ayoub et al. [6]
7	Si-based	15 kg/ha/20-40 nm	SiNPs	*Aspergillus spp.*	Phytopathogen resistance of maize	Activated the pre-regulation of phenolic compounds, resulting in increased plant resistance to *Aspergillus spp*.	Suriyaprabha et al. [71]
	Si-based	36 nm, 500 mg/L	Mesoporous silica nanoparticles (MSNs) with or without chitosan coating (CTS- MSNs)	*Fusarium Wilt*	Control Fusarium wilt in soil-grown watermelon	Disease severity was decreased by 40 and 27%, respectively, by MSNs and CTS-MSNs	Buchman et al. [10]

Table 1 (continued)

Sr. no	Nanomaterials (NPs)	Concentration/Size	Nano-Pesticides	Pest	Plant blight	Advantages	References
8	Other Nanomaterials		Silver (Ag)NPs	*Xanthomonas campestris PV.campestris*	Bacterial disease	Significant bacterial decrease	Rajesh et al. [58]
			Ag core- DHPAC shell nanocluster	*Phytophthoracapsici, Phytophthora nicotianae and Phytophthora colocasia*	Fungal disease	80% or more of the growth inhibition	Ho et al. [28]
			Iron oxide (FeO)NP	*R. Solani, B. Cinerea and F. oxysporum*	Fungal disease	60–80% of fungi are inhibited	Chhipa and Kaushik [13]
			Copper (Cu) NP	*Fusarium Sp*	Fungal disease	Antifungal activity	Bramhanwade et al. [9]
				Xanthomonas axonopodis Pv. punicae	Pomegranate bacterial blight	Presence of bacterial proliferation	Mondal and Mani [46]
			Chitosan NP	*Rhizopus spp. Colletotrichum capsica, Colletotrichum gloeosporioides and Aspergillus niger*	Disease in Chile	Mycelia's development is delayed	Chookhongkha et al. [14]

years [73]. A hybrid fertilizer made from nanomaterials and biofertilizers, nano-biofertilizers contain live microorganisms that are beneficial to plant growth, such as rice bacteria, Rhizobium, and blue-green algae (BGA), fungal mycorrhiza, Azotobacter, Azospirillum, and phosphate-soluble bacteria such as *Pseudomonas sp. E Bacillus sp.*

Using coatings of chitosan, zeolite, and polymers (nano capsulation) aids in increasing remediation efficiency, reducing fertilizer consumption, promoting the sustained release of slow-release agrochemicals, increasing production, and reducing soil structure issues, thereby preventing any related collateral problems [37]. Bioorganic nano-fertilizer particles provide several benefits for the soil and plant system, including increased nitrogen fixation, phosphate solubility, increased rate of plant growth hormone production, and improved plant microbiological condition. In the realm of nano-formulation, researchers in India demonstrated the usability of silver nanoparticles in agriculture and claimed that the same silver nanoparticles may be employed as nano-fertilizers or as a nano-capsules agent [37]. Other researchers investigated the biogenic production of a zinc nanoparticle using the bacterium Pseudomonas aeruginosa. They observed that the nanoparticles had excellent antibacterial activity, which makes these ZnONPs suitable for crop resistance in agriculture. Others suggested that in India, the use of nanomaterials like as silver or gold nanoparticles might be more active in improving nano-fertilizers. These nanoparticles function as the ideal plant grower when combined with biofertilizers including *Pseudomonas fluorescens*, *Paenibacillus elgii*, and *Bacillus subtilis* [37]. The field of nano-agricultural formulation is thriving and may be used to improve sustainable agriculture in a way that is both economic and ecologically important. Nanoparticle-based pesticides and fertilizers are being encouraged for use in field and laboratory studies to manage pests and illnesses. The findings so demonstrate that there are several possibilities to discover alternative techniques to safeguard human health and foster environmental well-being [78].

Nanotechnology is providing a fresh start for sustainable agricultural development. Because nanomaterials have demonstrated tremendous promise to minimize these difficulties, nanotechnology is being utilized to build nano-based smart formulations for pesticides and nutrition. The nano-capsules are a network of structural vesicles that contain the insecticides in the inner core. Nanomaterials offer great potential in nano-based pesticide formulation because of their huge surface area, tiny size, and changed target qualities. Their targeted coverage, water-dispersion, and insecticidal action are all greatly improved by these formulations. These nano-based pesticide formulations help in deposition, relief, delivering foliage to specific locations, and killing diseases or insects before they do damage after spraying. Additionally, it promotes foliar modification, or the deposition of droplets on

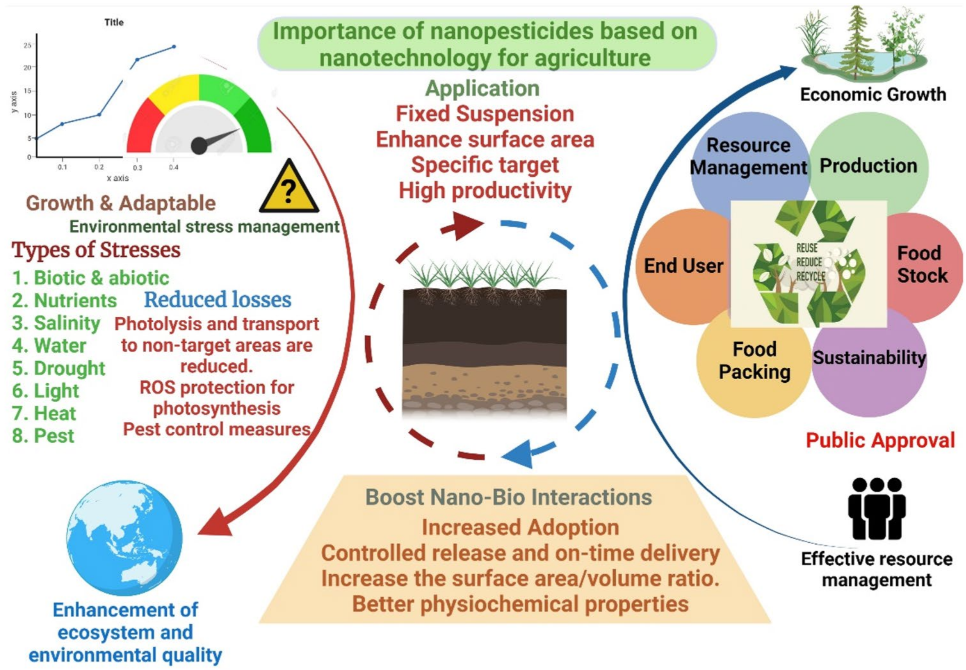

Fig. 2 Agriculture-relevant nano-fertilizers based on nanotechnology and use of nanotechnology effectively in agriculture for long-term sustainability

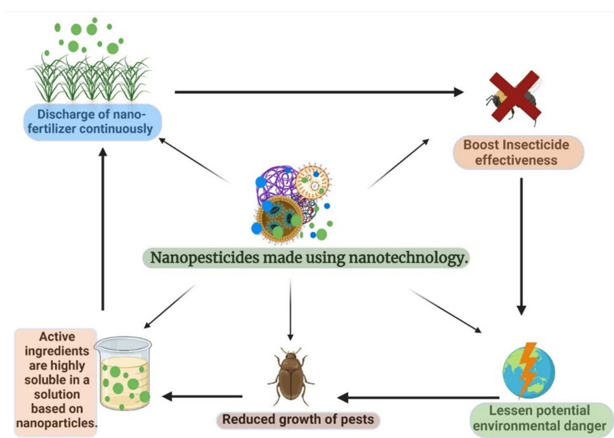

Fig. 3 Presents advantages of nano-based agrochemicals

the leaves and assists in the development of adhesion. One of the hot spots in the context of nanotechnical agricultural applications is the creation of these novel formulations based on nanoparticles [82]. Pesticide nano-formulations are created using a variety of organic or synthetic ingredients. Two methods can be used to enhance nano-pesticides: directly processing nanoparticles or adding nanocarriers to the pesticides' delivery mechanism.

When it comes to the effects of nano-formulations, there are certain common worries about bio-safety and degradation. Nanoparticles introduce a new class of polluting substances that endangers ecological equilibrium and is harmful to human health when they enter the food chain and surrounding systems. Therefore, it is essential that a particular study can be done on the pharmacokinetics, toxicological impact, and environmental behavior of nanomaterials. In order to evaluate their possible impacts on the safety and caliber of agricultural goods, we must look at the mechanism of interaction between plant nanoparticles. This will eventually lead to an upgrade of nano-pesticides and the environmentally responsible use of nanotechnology in agriculture. The efficiency of insecticide delivery to specific targets (insects and pathogens) must be increased, and insecticide release must be controlled based on the active concentration needed to kill pathogens, i.e., phytotoxicity reductions or limitations are two desired properties and goals of researchers for nanoparticle-based insecticide formulations. In order to provide agricultural chemicals, controlled release is advantageous since it prevents leaching losses, soil degradation, increases safety during the application, etc. [11]. Additionally, scientists want to improve the solubility and dispersion of fat-soluble molecules in aqueous solutions, the chemical stability of light-sensitive compositions by limiting photo-degradation, the bioavailability of substances, and their environmental friendliness [82].

The term "nano-fertilizer" refers to fertilizers that have at least one supplement controlled and slowly delivered to meet the objective fertilizer requirements of plants. Currently, these "bright composts" are seen as a viable alternative, even to the point where they are occasionally preferred above traditional manures [23]. A variety of nanoparticles, including metal oxides, carbon-based materials, and other nanoporous materials, are used to create nano-fertilizers, with the composition of the particles affecting how they behave. It frequently incorporates base-up (compound), organic, and hierarchical (physical) techniques [41].

For soil executives looking to reduce the overuse of conventional composts, nano-fertilizers have emerged as an excellent solution. Additionally, the component's slow distribution is providing opportunities for use in accordance with growth and natural conditions. Additionally, nano-fertilizers have demonstrated a remarkable ability to stimulate plant growth and utility, although take-up, movement, and collection of using nanoparticles are still not yet clearly defined. The mechanism of supplement delivery in nano-fertilizers gives them important benefits over conventional synthetic composts [40]. Through slow/control release devices, they limit the availability of supplements in crops. The coating or solidification of supplements with nanoparticles is connected to their slow delivery [68]. Due to the dependable long-distance supplement delivery to plants, cultivators might increase crop development by taking advantage of this slow supplement conveyance.

The use of nano-fertilizers in horticulture has a significant impact on achieving increased usefulness and protection against abiotic stressors. Therefore, boosting the use of nano-fertilizers in cultivation regions as well as agri-food biotechnology cannot be disregarded. In addition, the potential benefits of nano-fertilizers have sparked a great interest in increasing the capacity of rural harvests under the current conditions of environmental change. The main economic benefits of using nano-fertilizers are less draining and volatilization compared to using conventional manures [84]. While also having a significant favorable impact on yield and product quality, this invention has a tremendous potential to raise producers' net income. Although nano-fertilizers have produced some remarkable achievements in the world of agriculture, their relevance has not yet been aimed toward allurement. Prior to the widespread use of nano-fertilizers on a commercial basis, it is important to thoroughly research the vulnerability associated with the interaction of nanomaterials with the climate and the anticipated effects on human well-being. Future research should focus on gathering substantial data in these understudied areas in order to offer this smart wildness in sustainably based agriculture [17]. Consequently, research into the safety of nano-fertilizer application and the dangers of different nanoparticles used in the production of nano-fertilizers is necessary. Additionally, a thorough evaluation of the effects of nano-fertilizers in soils with diverse physio-substance qualities is necessary to recommend a specific nano-fertilizer for a certain yield and soil type. Composts and nano-biofertilizers based on biosynthesized nanoparticles should be further researched as a viable innovation to increase yields while achieving viability [42].

Nano-agri formulation's safety

The use of nano-agriculture formulations in agriculture is commonplace worldwide. However, toxicity of nanoparticles induced agrochemicals with plant species has been evaluated (Table 2). These boost crop outputs ensure global sustainability and aid in the reduction in agricultural system waste. The European Commission published its report on the examination of nanomaterials in food to determine if they pose a risk to human health earlier this year [38]. When used appropriately, there is no evidence to suggest that nano-based goods pose any dangers to human health or the environment, according to the EC's Committee on Risk Assessment (RAC). The agricultural industry in India is an important portion of the economy, and it relies on pesticides and fertilizers to produce food for both domestic and export use. India is also one of the world's major fertilizer users, consuming over 45 million metric tons each year. Because of the high consumption rate, land and water contamination and pollution have occurred, posing a serious concern. Toxic chemicals included in pesticides and fertilizers endanger consumers worldwide. To address this issue, we must reduce the usage of conventional pesticides and investigate more natural alternatives. As a result, trials are now being done to employ nano-formulations to boost farmer production while reducing fertilizer consumption [62].

The Indian Council of Agricultural Research (ICAR) conducted the first field experiment of agricultural nano-formulations on sugarcane, rice, groundnut, and cotton crops in 2001. Since then, a number of further field trials on a variety of crops have been done, including mustard, castor seed, chickpea, and sugarcane. Although commercial use has yet to emerge, patent rights have been sought in India and throughout the world [60]. Despite the fact that commercial trials have not yet taken place, nano-formulation has earned general acceptance in India. Billions of nanometer-sized particles are used to create nano-formulations. Because smaller particles may penetrate surfaces more easily than bigger particles, they are safer than larger particles. These nano-based technologies are subjected to safety tests to guarantee that they cause no damage to human health or the environment.

Sustainability agriculture livelihoods

Agricultural sustainability, biodiversity, and ecosystems are all negatively impacted by climate change. It poses a major risk to human health and has a negative impact on social and economic systems all over the world. Therefore,

Table 2 Toxicity of nanoparticles induced agrochemicals with plant species evaluated

Sr. No	Nanoparticles	Plant species	Effects	References
1	Fe_3O_4	*Lolium perenne L. & Cucurbita mixta cv. white cushaw*	Lipid peroxidation, elevated superoxide dismutase and catalase enzyme activity, and oxidative stress	Wang et al. [75]
2	CuO & Al_2O_3	*Solanum Lycopersicon*	Antioxidant enzyme activity is detected together with ROS-mediated membrane damage and membrane lipid peroxidation. DNA conformation by NPs is influenced by both intercalative and non-intercalative mechanisms. Al_2O_3-NPs produced less alteration in TmDNA conformation. Macromolecular changes in the amide-I and II of proteins and carbohydrates, a concentration-dependent decrease in fresh and dry biomass, and CuO being more hazardous than Al_2O_3	Ahmed et al. [2]
3	TiO_2 & ZnO	*Hordeum Vulgare L*	ZnO was more hazardous than TiO_2, although no alterations in seed germination or root elongation have been noticed. The antioxidant enzyme activities are diversely altered	Dogaroglu and koleli [19]
4	TiO_2 & CeO	*Lactuca sativa, Brassica oleracea, Z. mays, Avena sativa*	There were species-dependent impacts on plants, varying phytotoxicity based on the nanoparticle type, significant alterations in seed germination but no acute toxicity, and lettuce, onion, ryegrass, and tomato were effective for both nanoparticles	Andersen et al. [4]
5	CuO	*Glycine max cv. kowsar*	With 25 nm CuO NPs in soil, particle size- and concentration-dependent toxicity changed antioxidant indicators	Yusefi-Tanha et al. [80]
6		*Brassica oleracea var. botrytis & Solanum lycopersicum*	CuO NPs at concentrations of 100 and 500 mg L^{-1} reduced total chlorophyll and sugar content, increased lipid peroxidation, electrolyte leakage, and antioxidant enzyme activity, increased superoxide and hydrogen peroxide generation in leaves, and deposited lignin in roots	Singh et al. [66]
7		*Hordeum sativum distichum*	Root morphology, cell wall, epidermis, cortical layers, and vascular bundles are all affected by ultrastructural changes in chloroplast, vacuoles, mitochondria, and stomata, which reduces root and shoot length	Rajput et al. [59]
8	Ag	*Vicia faba*	Modifications to stomatal conductance, PSII activity, and CO_2 assimilation	Falco et al. [22]
9	ZnO	*Brassica napus*	At higher concentrations (250 and 500 mg/L), this substance prevents root growth, but has less drastic effects on shoot elongation	Mousavi Kouhi et al. [47]

Table 2 (continued)

Sr. No	Nanoparticles	Plant species	Effects	References
10	ZnO	*Solanum lycopersicum*	The levels of total phenols, flavonoids, -carotene, and lycopene in fruits were dramatically decreased, as were the levels of increased APX and SOD activity, lipid peroxidation in roots caused by the production of H_2O_2, and alterations in the contents of non-enzymatic antioxidants	Akambi-Gada et al. [3]
11	FeO	*Lemna minor*	High iron oxide NP concentrations altered the process of light absorption, produced ROS in excess, and reduced the amount of chlorophyll and the chl a/chl b content ratio	Souza et al. [70]
12	CuO, TiO_2 and Fe_2O_3	*Triticum aestivum*	Human essential amino acids were decreased by CuO treatment, along with the levels of Fe and Zn. TiO_2 treatment enhanced the concentration of amino acids overall	Wang et al. [77]
13	Se	*Capsicum annuum*	WRK1 and bZIP1 transcription factors were increased, which affected the plant's growth metabolism and anatomy. DNA hyper-methylations were also brought about by the epigenetic modifications	Sotoodehnia- korani et al. [69]
14	Se	*Mormordica charantia*	More concentrations result in stem bending, decreased root meristem function, and severe toxicity. They also alter DNA cytosine methylation, which reflects epigenetic alteration, and they activate the peroxidases and catalases, which disturb the xylem conducting tissues	Rajaee Behbahani et al. [57]
15	CeO_2	*Lactuca Sativa*	The generation of biomass and plant growth are dramatically worsened by higher concentration treatments. The activity of superoxide dismutase, peroxidase, and malondialdehyde was disturbed	Gui et al. [27]

embracing sustainability in food production is crucial to overcoming these difficulties. One way to preserve sustainability in pro-poor agricultural communities in low-income nations is to practice sustainable agriculture. It helps farmers to meet present-day and future needs for food, fiber, health, and ecosystem services [43]. In developing nations, agriculture is the primary source of income for most farmers and non-agricultural families. In India, subsistence and agricultural sustainability are related.

It is impossible to overlook the serious problem of poverty on the planet. The majority of the poor reside in underprivileged regions with challenging agricultural climatic circumstances such as limited rainfall, poor soils, a short growing season, steep slopes, and a lack of infrastructure and support services, which is much more obvious in rural areas [72]. Agriculture that is sustainable is environmentally benign, technologically possible, socially acceptable, and commercially viable (FAO 1991). In order to ensure the achievement and ongoing satisfaction of individual needs for both the present and future generations, the Food and Agriculture Organization (FAO) has demonstrated sustainable agriculture, which manages and maintains the resource base and guides institutional and technological changes.

The food system's closest ecosystem partner and one that is best managed globally is agriculture. The expansion of agriculture is seen as crucial for achieving the objectives of reducing poverty and ensuring domestic food security in a country like India, which is largely rural. For the purpose of enhancing rural residents' quality of life, sustainable agricultural expansion is required. It is important to widen and improve the methods used to support agricultural expansion that is sustainable. The only industry that can provide food for humans using intermediate and final inputs and existing technology is agriculture. Consequently, it is essential to have current agricultural expertise. Even if they have certain relative advantages in the agricultural process, emerging nations nevertheless struggle with a lack of a strong emphasis on food goods. Even though there is a wealth of knowledge on specific nanoparticles, the toxicity level of many NPs is still unknown [32].

Agronomic practices and soil health can be improved by nanotechnology. Using nanoscale carriers and compounds has the potential to improve the efficiency of fertilizers and pesticides, reducing their use without compromising productivity. Nanoparticles such as Ag, Au, Zn, TiO_2, ZnO, SiO_2, and MgO, which are widely used in food processing, for their facile penetration into the cell, may cause undesirable responses inside many organs of humans, animals, and plants. Using greener production, as well as simple and inexpensive techniques for degrading and removing existing nanomaterials from attack sites could reduce such hazards in future studies [55, 83]. Other properties of engineered NPs that can influence their toxicity include their chemical compositions, shapes, surface structures, surface charge, and behavior. The use of nanomaterials not only facilitates the direct catalysis of waste and toxic materials degradation but also assists in improving the efficiency of microorganisms. In bioremediation, toxins and harmful substances are broken down or removed from agricultural soils and water by living organisms. Furthermore, other terms are also commonly used, including bioremediation (use of beneficial microbes), phytoremediation (use of plants), and myco-remediation (use of fungi and mushrooms). Microorganisms can, therefore, remove heavy metals from soil and water by bioremediation in an environmentally safe and efficient manner. Agricultural bioremediation thus plays a significant role in sustainable remediation technologies for resolving and restoring soil conditions. It is an interesting phenomenon to consider the nano-nanointeraction to remove toxic constituents from agricultural soils and make them sustainable [18].

By defending plants against harmful elements like plant diseases and insects, pesticides are utilized to increase and improve agricultural productivity and efficiency. The usage of pesticides, on the other hand, has been shown to be detrimental to human and animal health and poisonous to the environment. Consequently, several pesticides are prohibited by national or international agencies. This entails a number of important and crucial concerns, such as the widespread use of pesticides at high concentrations, which degrade the environment, increase bioaccumulation, render the soil infertile, and alter its microbiota. Future research should focus on using nanomaterials to protect plants and provide food. Since it is generally known that insect pests predominate in agricultural fields and in the goods made therefrom, NPs may play a critical role in the management of insect pests and host infections. A new pesticide formulation with nano-encapsulation offers improved solubility, specificity, permeability, and stability with gradual release characteristics [45] (Fig. 2).

Advantages of technology smart-nano-system

Role of nanotechnology for enhanced food security

Nanotechnology (NT), one of the many scientific advancements, is a quickly developing field that has the potential to transform food systems [67] and improve inadequate food security conditions. Water safety, agricultural productivity, soil health, and food quality throughout distribution and storage are the primary factors of food safety. Green technologies encompassing all elements of the agricultural supply will be revolutionized by the incorporation of nanotechnology in disciplines like agricultural biotechnology. All present legal, social, ethical, and environmental elements will be affected more quickly and significantly as a result. The most thoroughly studied topic is thought to be nanoparticles, followed by nano-filtering techniques and nano-capsules. Particles and capsules are examples of formulations that are known to provide greater control, support target distribution, and enhance overall functional efficiency. Utilize the particles and capsules as inputs for pesticides, including bio-insecticides, fertilizers, and better management techniques [35]. Applications of nanotechnology for promoting food safety in India include the following: (i) slow-release and effective dwarf water fertilizers, (ii) fertilizers used by plants, (iii) nanocides, which are insecticides encapsulated in nanoparticles to control release; (iv) nano-emulsions for better efficiency; (v) provision of medicines and food for livestock; (vi) nanoparticles for soil dissolution and conservation; (vii) nano-brushes. When preparing food, nanoparticles can be quite important. Nanobium compounds and nanocomposites are employed in plastic film coatings for food packaging. Cleaning, processing and packing of food equipment all employ nano antimicrobial emulsions. Together, these technologies strengthen the factors that affect food security and help India's efforts to promote it. Food security is a crucial component of Indian policy. To create a sustainable food safety system, emerging technologies like nanotechnology can concentrate on the four primary determinants of food safety. Studies show that nanotechnology, as opposed to biotechnology and green revolution technologies, has a bigger influence on food security [35].

Enhanced food quality

Nanotechnology has brought in many advancements in the field of food development. A variety of new systems have been developed to deliver nutrients and bioactive, encapsulate flavor and texture, control microbes, and enhance food packaging and processing. There has been a major improvement in the design of specific, sensitive biosensors that can be used to determine contamination, pathogens, allergens, and degradants that impact food quality and safety. In addition, nanotechnology has accelerated the development of food ingredients. Natural dietary ingredients including proteins, lipids, and other substances are employed to make fibers, solid–liquid particles, multilayered particles, and unique architectures [15]. The intake, effectiveness, speed of digestion, metabolism, and bioavailability of foods treated at the nanoscale in the human body would all rise. Additionally, they strive to improve tastes, lessen fat, sugar, salt, and preservatives, as well as address food-related illnesses including diabetes, obesity, and blood pressure. Nanoscale materials are also useful in food modification, such as lowering carbon dioxide leakage from carbonated beverages and limiting oxygen ingress or bacteria development to make food safer and fresher. Plastic wrapping that warns against food spoiling is another application of nanoscale materials, as is detecting pesticides, salmonella, and other pollutants in food before distribution and packing. Among nanocomposites, polymer compositions containing clay nanoparticles are thought to be the first to limit gas penetration and increase gas barrier characteristics. Polymer nanocomposites containing metal nanoparticles have been produced for antimicrobial packaging, UV absorption, and/or strength and resistance. Nano-silver has antibacterial properties. Metal oxides, such as silver (ag), are utilized in nanoparticles to preserve food for extended periods of time and to limit microbial development. Copper has also been demonstrated to be an effective humidity sensor, while titanium oxide has been shown to be abrasion-resistant [15].

Disadvantages of technology smart-nano-system

Nanotechnology is increasingly used in agricultural practices and food products, causing concern among a majority of society due to the multiple antagonistic effects of different nanoparticles. Due to the small size of nanoparticles with large surfaces, nanotechnology poses a potential threat due to its ability to penetrate cells to reach quite distant areas of the body and cause potential toxicity [49]. When nanoparticles are exposed to the agro-environment, they undergo a series of modifications. One of the most concerning aspects is the interaction of nanoparticles within the human body. Nanoparticles can produce oxidative damage and provocative responses, and waste nanoparticles have the potential to cause toxicity [7]. Through cutaneous contact, ingestion, or inhalation, nanoparticles can enter the body. As their release from tainted food or the environment raises concerns, there is a great deal of nanomaterial use in food packaging. However, there is little information known about the migration of nanoparticles from packaging materials into food and their ultimate toxicological effects [53].

Inappropriate usage, unidentified risks, and possible negative effects on the environment and human health are the most dangerous features of nanotechnology. Despite the fact that there is no quantifiable way to determine whether the benefits outweigh the risks, the actual and prospective risks of uses of nanotechnology generate significant concern. Without fully understanding the potential effects of their breakthroughs, scientists continue to search for useful uses for nanoparticles. One concern is the creation of a tiny, undetectable biological or atomic weapon by purposely manipulating particles to cause bodily harm to one or more people [50]. Another ethical worry about the abuse of nanotechnology is the potential to change human genetic makeup by designing certain features. Due to their small size and potential to cross the blood–brain barrier, nanoscale particles may be toxic to humans and cause mass poisoning or unintended neurological effects. Nanoparticles may also pass through a mother's placenta and contribute to the formation of free radicals, which can cause negative health effects [51]. It is unknown to scientists if prolonged exposure to nanoparticles might harm people by slowly poisoning them and leading to long-term health issues including the danger of inhalation, which can seriously harm the lungs and have potentially cancer-causing effects. Titanium oxide nanoparticles, which are included in sunscreens, may cause cancer if they are absorbed via the skin [65], or they may negatively affect the ecosystem by contaminating the water supply or harming wildlife. Nano-contamination is a form of pollution brought on by the scale of nanotechnology. The ability of substances to change at the molecular level has a significant potential for use. Nanomaterials have been the subject of preliminary investigations that have resulted in significant health risks, toxic consequences, and tissue damage that has reached all essential organs. Because of their antimicrobial properties, silver nanoparticles are used in another emerging method to deliver fertilizers to plants. However, studies have found that this method poses a serious threat to the ecosystem because it can damage membranes, reduce grass growth annually, and reduce algal photosynthesis [44].

Conclusion

Nano-biotechnology works to create biofertilizers, that have a new minimal cost, are environmentally friendly and improve agricultural productivity, crop outgrowth, and soil goodness. The development of nano-biopesticides and nano-biofertilizers from various sources such as plants, microbes, and their derivatives are an eco-friendly approach and offer benefits of slower release, prevention of degradation, longer performance, and biodegradability. Chemical fertilizers and pesticides must be replaced with eco-safe alternatives. The properties of nanoparticles can be altered compared with their bulk analogs, offering superior application strategies for pharmaceuticals, medical products, industrial applications, and agricultural products. As a result of the development of polymer-based nano-encapsulations, active ingredients can be delivered with greater control while reducing premature degradation caused by the environment. Specifically, nanoparticle-based formulations have the following benefits: higher water solubility; safety of active ingredients from early deterioration; prolonged pesticide delivery; enhanced uptake by target organisms; small dosages due to controlled release on receiving proper stimuli; enhanced surface properties, such as leaf adhesion and penetration; reduced pesticide losses through leaching and runoff; and auto-decoction. In the agriculture and food industry, nanotechnology can be used to eliminate the harmful effects of conventional agrochemicals and practices by moving toward a modern application of nanotechnology with great potential and high reliability.

Future prospects

Efficiency assessment and exploring the antimicrobial potential of Nano-Agriculture formulations for preservation of the cash crops. Due to various mechanisms, metallic nanoparticles can preclude or overwhelm the multidrug resistance and biofilm formation and thus can help in abating or avoiding microbial drug resistance. Metallic nanoparticles are utilized as efficient antimicrobial, antifungal, antiviral, and anti-inflammatory agents.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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