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Exploring the antifungal activities of green nanoparticles for sustainable agriculture: a research update

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Abstract

Green nanotechnology has significant potential for use in agriculture particularly due to their antifungal properties, ability to control fungal diseases and reduce the reliance on chemical fungicides. Biotic stresses in agriculture have caused widespread damage worldwide, and green NPs provided eco-friendly alternatives to traditional chemical treatments, which are frequently toxic and harmful to the ecosystem. Green NPs could become an important tool in modern agricultural practices and environmental remediation if appropriate research is conducted to identify cost-effective production methods as well as safe and sustainable applications. In order to understand the potential of green NPs for sustainable agriculture and identify potential risks, research is ongoing into the effectiveness in agriculture sectors. Research update on green NPs is presented in this paper using data published on science direct over the last 15 to 20 years to clarify and understand the antifungal mechanisms of green metallic NPs, carbon and graphene nanotubes, nanocomposites as well as other type of nanomaterials. These green NPs are found to be more effective against pathogens on crops and humans than conventional fungicide approaches. They are very effective against fungi that affect cereal crops, including *Fusarium oxysporum*, *Botrytis cinerea*, and *Candida species*, etc. The green NPs developed using green synthesis methods are both cost-effective and environmentally friendly. Moreover, research is also required to identify the best methods for applying green NPs for crop production and sustainable agriculture. Furthermore, research should be undertaken to establish the most cost-effective methods of making and deploying green nanoparticles at a large field size study where there is fungal attack that diminishes agricultural output and affects global crop production.

Keywords Green nanotechnology, Metallic NPs, Antifungal activity, Biotic stresses, Sustainable agriculture, Crop production

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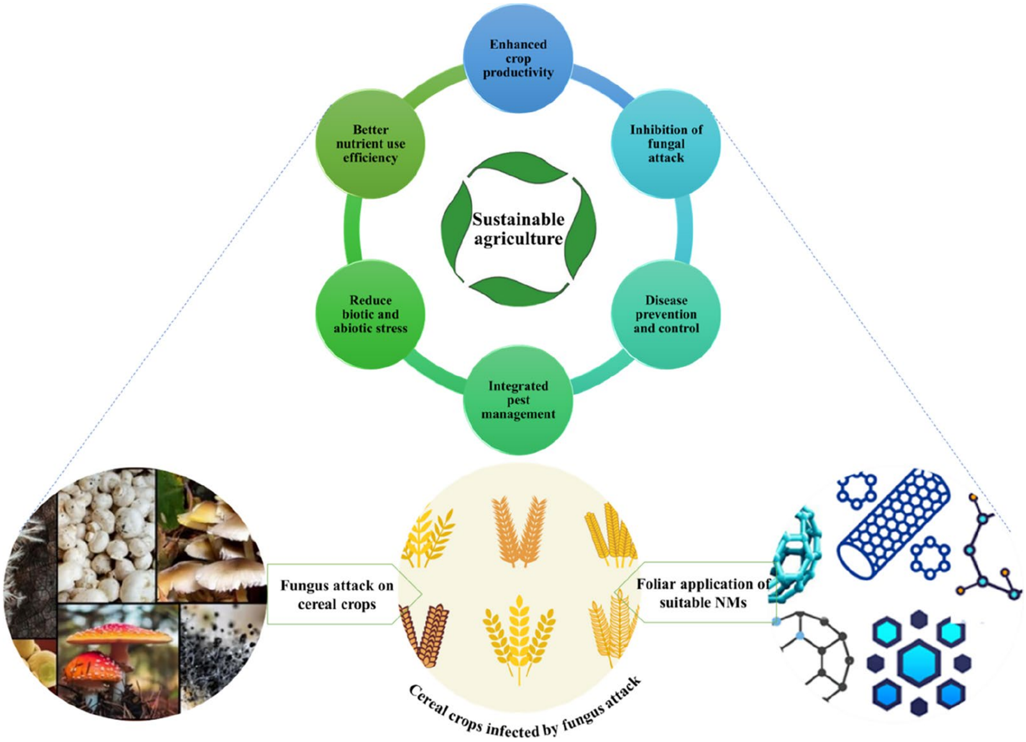
Graphical Abstract



Green nanotechnology: an overview

There is an imbalance in the world's natural resources as a result of population growth and exploitation of ecosystem. Nanotechnology, according to researchers, can improve products by improving their performance, lowering manufacturing costs, and increasing resource efficiency. It is one of the most rapidly rising fields in science and technology. Nanotechnology can create nanoparticles (NPs) with higher surface-to-volume ratios and a variety of chemical and physical characteristics. Nanoparticle are widely employed in chemistry, energy, healthcare, and cosmetics for environmentally friendly applications. Metal and semiconductor NPs include oxides, nitrides, and sulphides [1–3]. The creation of nanoparticles by living cells, especially via plant resources is the subject of the newly developing scientific field known as "green nanotechnology". Numerous sectors rely on this field, including electronics, biotechnology, nuclear energy, fuel and energy, and pharmaceuticals as well as for the remediation of various environmental ailments [4–6]. Since biological procedures using green synthesis tools are safer, more environmentally friendly, non-toxic, and more economical than other similar approaches, they are better suited for synthesizing nanoparticles between 1 and 100 nm. The top-down and bottom-up approaches use different physical, chemical, and biological processes to create the metal nanoparticles [7, 8]. Following Fig. 1 explores the green synthesis routes along with the potential applications of green nanotechnology.

Greenly produced NPs have been shown to enhance the performance of solar cells, photocopiers, xerography, rectifiers, antioxidants, and photocatalysis [9]. According to Pansambal et al. [10], green-produced cerium oxide nanoparticles have antioxidant, antidiabetic, anticancer, antibacterial, and antifungal properties in addition to photocatalytic dye degradation. Potential photocatalytic, antioxidant, and antibacterial properties of green-produced stannic oxide nanoparticles make them useful for improving environmental and human health applications [11]. Applications in biomedicine and the environment are being developed with green-produced silver chloride nanoparticles [12]. Different plant parts are used to create green synthetic metal nanoparticles, which are also generated using economical, non-toxic, and environmentally beneficial processes. In contrast to different physical and chemical methods, environmentally friendly produced nanoparticles perform more actively in the removal of dyes, antibiotics, and metal ions from

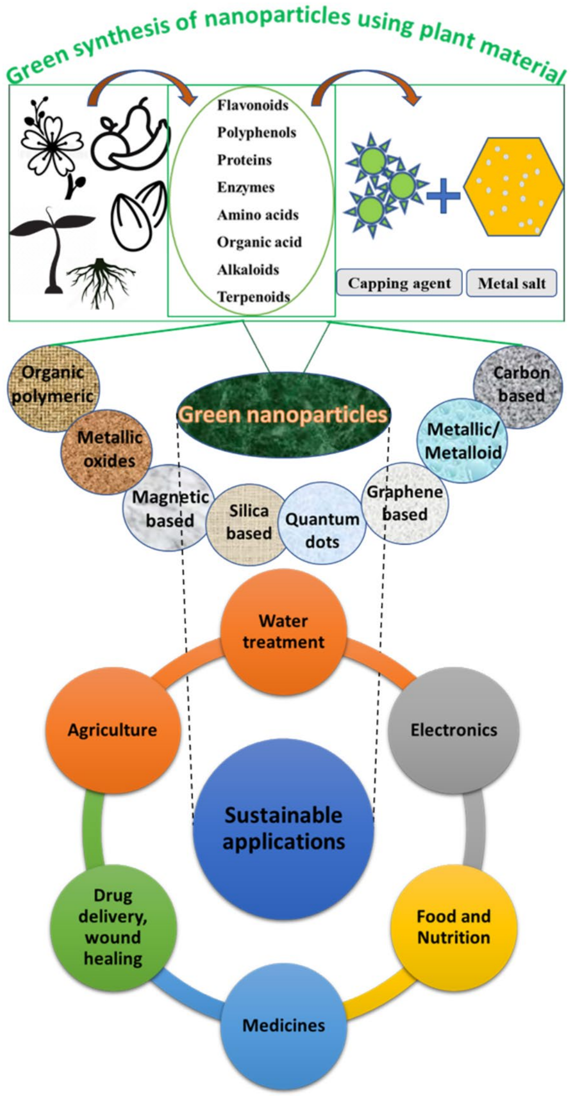


Fig. 1 Mechanism of green synthesis of nanoparticles by using plant materials and its sustainable applications in various sectors

the soil and water media. The most effective way to make nanoparticles is by green synthesis, which also happens to be a cost-effective, environmentally friendly, and very stable process. In environmental and biological applications, green synthesis techniques respond more favorably [13, 14]. Numerous phytochemical substances with oxidation–reduction properties, such as flavonoids, phenolics, terpenoids, and polysaccharides, are found in plants. For this reason, they are best used in the environmentally friendly creation of nanoparticles. The process of creating stable nanoparticles requires precise understanding of the phytochemical components, hence the synthesis of phytochemical compounds for nanoparticles is not a general process [15, 16]. Most people feel that the important actors in the creation of environmentally friendly nanoparticle manufacturing are plant secondary metabolites, notably polyphenols, phenols, and other plant materials that participate in the synthesis process. According to [17], green synthesis approach is more sophisticated, repeatable, safe, and inexpensive. Comparing plant-based green manufacturing of nanoparticles to other comparable biological processes involving actinomycetes, bacteria, fungi, and algae reveals certain advantages [18]. The presence of considerable phytochemicals in these artificially manufactured green nanoparticles raises concerns for numerous plant parts, including the roots, stem, leaf, seed, and fruit [19]. In various plant portions, squeeze, wait, and apply salt solutions after cleaning with tap or distilled water to produce plant-synthesized nanoparticles. Using this method, metallic salts were added, and then the nanoparticles were eliminated using the required laboratory procedures. Among the industries that employ green nanoparticles are agriculture goods, food, aquaculture sciences, personal hygiene, medicine, and nano-enabled technology.

Green nanotechnology and agriculture

Green nanotechnology research has demonstrated a considerable potential to alleviate major barriers to reaching sustainable agricultural production objectives. Utilizing environmentally friendly materials has the potential to transform food systems and address the global food security issue of today. With the magic of nanotechnology, it has the power to change modern agriculture from the period of genetically modified crops to the exciting new era of atomically changed organisms [6, 20–23]. The excessive use of chemical fertilizers for higher yields give rise to growth of insects and microbes causing fungal diseases in great numbers in the present day unsustainable agricultural practices. These fungal attacks can possibly impact both the crops growth and the crops yield imposing economic losses to the farmer's community.

On the other hand, the innovative GNT is based upon the applications of nanotechnology principles and techniques applied in an eco-friendly mode for effective control of fungal activities of various pathogens in agriculture. The GNT involves the use of suitable materials on a microscopic scale of (0.1–100) nm size to effectively control the desired ailments from the start to the maturity of the plants. Hence, their applications in agriculture can enhance crop production and improve resource efficiency, offer innovative and eco-friendly approaches to control all possible antifungal activities in plants [24–26]. It is noticed during the research, that the use of GNT applications can greatly increase the stability of crops by reducing the losses due to abiotic and biotic stresses, producing higher crop yields by curtailing the production costs in agriculture [27]. The GNT involve the applications of following novel nanoparticles techniques in the field of emerging agriculture. The nano-coatings on seeds can speed up germination rates, protect against pests and diseases, and can provide controlled release of nutrients during early growth stages of plants in agriculture [28].

The nanotechnology can contribute to the development of efficient nano-based water filtration and adsorbent systems that ensure pathogen and toxic free clean water for irrigation purposes. A lot of inorganic materials, such as heavy metals, were present in the wastewater from the industries, posing serious health hazards to people. Nanobased filtration alleviates those effects. This technology can also be used to purify water from other sources, such as rivers and lakes. It can provide a cost-effective and efficient way to clean contaminated water and make it safe for consumption [29–34].

Numerous studies have demonstrated the potential of green nanotechnology to regulate stress-induced changes in plants. Moreover, the regulated and targeted release of nano-pesticides has been shown to be a highly successful method of removing biotic stressors in agriculture, particularly for wheat crops [35, 36]. Some possible green NPs measures for the agriculture sector's sustainable farming practices are shown in Fig. 2 below. These actions include preserving water, enhancing soil health, and using fewer toxic pesticides and fertilizers. Using sustainable energy sources, including wind and solar energy, can also aid in lowering carbon emissions. These properties and futuristic approach of green nanotechnology can enhance the crop production in agriculture [37, 38]. The development of nano-scale formulations for pesticides can improve their efficacy and reduce the amount of chemicals needed. Nano-encapsulation of active ingredients enhances targeted delivery and reduces the environmental contamination to the minimum level. The nano-based fertilizers aim to enhance nutrient uptake by plants, increasing the efficiency of nutrient utilization. Moreover, the controlled release mechanisms in nano-based fertilizers can supply necessary nutrients to plants for wider periods and hence reducing the need of their frequent supply to the plants. Moreover, the use of nanocarriers can improve the efficiency of delivering various agricultural inputs primarily pesticides, nutrients to the plants [39–42].

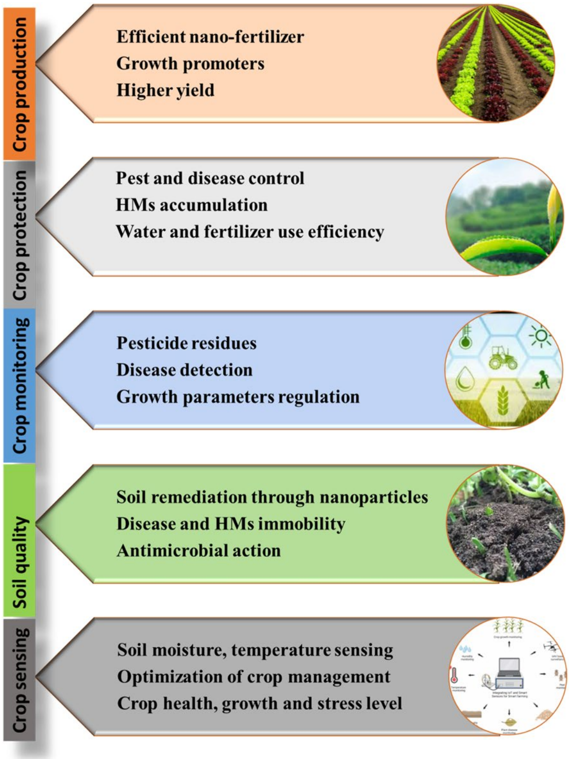


Fig. 2 Role of green nanoparticles for the agricultural services as crop production, crop protection, crop monitoring, soil quality, and crop sensing

Antifungal activities of green nanoparticles

Techniques involving plants with nanotechnology called "green nanotechnology" offers an efficient, eco-friendly management and control of these fungal pathogens in agriculture. Plant-based nanotechnology is a cutting-edge approach that will undoubtedly bring an era of agricultural technology innovation to solve such issues. Nanoparticles based on phyto-extracts demonstrate the potential of antimicrobial activities for effective fungal pathogen control compared to conventional fungicides. In addition to ensuring plant health, nanoparticles satisfy agriculture's growing need for high output. The limits of chemicals and the potential of green nanoparticles, which provide fresh approaches to managing fungicides that cause fungal illnesses in agriculture, are the primary topics of this paper. Recent research showed that the rise of fungal diseases in plants resulted in economic losses in the agriculture. Chemical fungicide sprays are not an environmentally acceptable way to treat fungal illnesses since they pollute the environment and pose a risk to human health as well as other biotic life forms. However, these chemical fungicides appear overused due to their affordability and ease of application [43]. According to Moore et al. [44], fungi account for 70–80% of the losses brought on by microbial diseases. It is believed that there are around 1.5 million species of kingdom fungus, and most of these fungal pathogens cause plant illnesses and production losses. Fungal infections have been responsible for agricultural losses exceeding 200 billion euros annually [45]. Animal pests account for around 18% of agricultural crop losses, with microbiological diseases and weeds accounting for 16% and 34% of losses, respectively. However, it is utmost essential to consider potential environmental and health impacts while employing green nanotechnology in agriculture. The overall sustainability of agricultural practices requires careful development of GNT and essentially should be done thorough valid risk assessments before its field application.

A variety of fungal infections were effectively inhibited by the ZnO NPs made from *Parthenium hysterophorus* plant extracts. For example, ZnO NPs based on parthenium start to significantly slow down the growth of *A. flavus* and *Aspergillus niger* pathogens, respectively [46]. ZnO nanoparticles, which were produced with the help of *Syzygium aromaticum* bud extracts, shown efficacy against *Fusarium graminearum*, a pathogen that typically inhibits the growth of mycelial cells and the synthesis of mycotoxins such as zearalenone and deoxynivalenol. At the same time GNT treatments can raise lipid peroxidation, reactive oxygen species (ROS) production and lower ergosterol matters of fungal membrane which is highly damaging to established pathogens in agriculture [47].

Downy mildew, produced by *Plasmopara viticola*, reduces the crop production that effects the food security. This illness can be efficiently managed with a nano-composite of graphene oxide (GO) and iron oxide (Fe_3O_4) known as GO-Fe_3O_4. Pretreating leaf discs with this nano-composite before inoculating with *P. viticola* sporangium significantly reduces spore germination, most likely by restricting water routes in the sporangia. While ordinary Fe3O4 and GO have limited control on spore germination, the nano-composite is far more powerful. Graphene oxide coated with silver nano-composite can cause antifungal effects by interacting with fungal cell membranes and disturbing their bonding severely as in case of pathogen *F. graminearum* [48].

The use of silver nanoparticles (Ag NPs) has demonstrated a favorable impact by establishing direct contact between the Ag ions and the pathogen's spores and germ tubes, so stopping their negative influence. This confirms that Ag NPs are capable of curbing a variety of illnesses caused by plant pathogenic fungi. So AgNPs provide strong antifungal properties by disrupting fungal cell membranes and halting their cellular processes for further growth. They are effective against a broad spectrum of fungi, making them valuable in agriculture [49]. The Ag NPs are commonly utilized for sterilization processes, such as waste-water treatments and water sanitization, because of their antimicrobial qualities [50]. By employing the green chemistry approach, Ag NPs may be synthesized to regulate the detrimental effects of certain fungal diseases. For example, Krishnaraj et al. [49] tested the efficacy of Ag NPs at varying concentrations against a variety of fungal plant pathogens, such as *Rhizoctonia solani*, *Macrophomina phaseolina*, *Alternaria alternata*, *Curvularia lunata*, *Botrytis Cinerea,* and *Sclerotinia Sclerotiorum*, using green AgO NPs utilizing the leaf extract of *Acalypha indica*. Amazingly Ag NPs with a concentration of 15 mg showed a remarkable inhibitory activity against all above pathogens in the field of agriculture. In a different study, Ag NPs (30 ppm) prepared from $AgNO_3$ (5 mM) solution using Argemone mexicana leaf extract were shown to be extremely poisonous to the pathogenic fungus *Aspergillus flavus* [51]. Also, Ag NPs can be manufactured by using seeds extract of *T. peruviana* (10%) mixed in chemicals of $AgNO_3$ (1 mM) in the presence of sunlight or autoclave method or combination of both techniques. The performance of Ag NPs is much bigger by careful treatment which may inspire the direct contact of Ag ions with germ tubes and spores to control effectively pathogen and fungi activities in agriculture [49]. The following Table 1 illustrates the use of several NPs for successfully reducing fungal attacks on different crops. The NPs used are commercially available and have proven their effectiveness in reducing the attack of fungi on crops. These NPs are applied directly to the plants, where they act by inhibiting the growth of fungi. In some cases, the NPs can also be used to prevent future fungal attacks.

In the field of plant pathology in agriculture, the green NPs may be effectively utilized to treat a range of fungal infections [106, 107]. Kumar et al. [108] reported on the use of Aloe Vera (*Aloe barbadensis Miller*) leaf extract for the production of Cu NPs, which shown antioxidant properties for plant diseases, including blackberry fruit. Also use of Citron juice (The Citrus Medica) for the biosynthesis of Cu NPs confirmed strong inhibitory properties against the pathogens of *F. graminearum*, *Fusarium*, *culmorum*, *F. oxysporum* and *culmorum Fusarium*, respectively. However, they proved less effective against pathogens of *F. graminearum* and *F. oxysporum*, respectively [109].

The study of green synthesis of Cu NPs with the stem extract of clove (*Syzygium aromaticum*) displays an outstanding antifungal action against pathogens *Aspergillus niger*, *Aspergillus flavus* and *Penicillium* spp., respectively [110]. Further successful control of fungal activities by green Cu NPs was reported against the harmful phytopathogens including *Penicillium digitatum, Fusarium oxysporum, Phoma destructiva, Phytophthora cinnamon, Alternaria alternata, Pseudomonas, Curvularia lunata, syringae,* and *Alternaria alternata*, respectively [111].

The gold nano particles (GNPs) can be successively synthesized by green method using variety of fresh leaves extract of *Memecylon edule* [112], *Punica granatum* [74], *Capsicum annuum* [113], *Magnolia kobus* and *Artemisia dracunculus* [114]. They are also synthesized by floral

Table 1 Antifungal activities of green nanoparticles synthesized from the plant materials

Types of NPs	Method of synthesis	Characterization (shape and size)	Fungus specie	Targeted crop	Evaluation method	References
ZnO	Green synthesis by *Eichhornia crassipes*	Hexagon, 20 nm	*Phoma* sp.	Sorghum, beans	In vivo	[52]
Fe_3O_4@SiO_2 Cu (II) magnetic NPs	Biological synthesis by Didymella pinodes	–	*Fusarium avenaceum, Didymella pinodes*	Legumes, cereals	In vitro, in vivo	[53]
Au NPs	Peganum harmala L	Oval, 42–72	*Candida albicans*	Cereals, legumes	In vitro	[54]
Ag NPs	Peganum harmala L	Spherical, 12–35	*Candida albicans*	Cereals, legumes	In vitro	[54]
TiO_2 NPs	Green synthesis by Trianthema portulacastrum, Chenopodium quinoae	Spherical, 40–60 nm	*Ustilago tritici*	Wheat	In vivo	[4]
SeNPs-AGL, SeNPsCOF	Green synthesis by *Amphipterygium glaucum and Calendula officinalis* flowers	8, 134	*Fusarium oxysporum and Colletotrichum gloeosporioides*	Cereals, fruits	In vivo	[55]
CeO_2 NPs	Chenopodium quinoae	Round clusterous, 7–10 nm	*Ustilago tritici*	Wheat	In vivo	[56]
Ag/CuO and Ag/TiO2 NPs	Green synthesis by Caesalpinia pulcherrima flowers	Tetragonal crystal structure, 6 nm and 8 nm	*Candida albicans, Pseudomonas aeruginosa,*	–	In vitro	[57]
ZnO/TiO_2	Biological method	–	*Candida albicans*	Cereals, legumes	In vitro	[58]
CeO NPs	Green synthesis by Malia azedarach	Spherical, 42 nm	*Puccinia striiformis*	Wheat	In vivo	[59]
Ag NPs	Green synthesis by Malva parviflora	Spherical, 50.6	*Hebeloma rostratum, Fusarium solani, Fusarium oxysporum*	Corn	In vitro	[60]
Ag NPs	Green synthesis by hay bacillus	Spherical, 22.33–41.95	*Cyrtomium falcatum*	Corn	In vitro	[61]
Ag NPs	Green synthesis by Penicillium verrucosum	Spherical, 10–12	*Fusarium chlamydosporum and Aspergillus flavus*	Wheat	In vitro	[62]
Ag NPs	Green synthesis by Nigrospora oryzae	Spherical, 3–13	*Fusarium sambucinum, Fusarium semitectum and Fusarium sporotrichioides*	Wheat	In vitro	[63]
Cu	Green Synthesis by Talaromyces pinophilus	Spherical, 10	*Aspergillus fumigatus, Aspergillus flavus and Aspergillus niger*	Corn	In vitro	[64]
Cu	Green Synthesis by Celastrus paniculatus	Spherical, 5	*Fusarium oxysporum*	Rai	In vitro	[65]
Ag NPs	Green Synthesis by Alternaria species	Spherical, 3-10 nm	*Fusarium oxysporum, Fusarium moniliforme, Fusarium tricinctum*	Maize	In vitro	[66]
Ag NPs	Green method by using Satureja hortensis	–	*Fusarium oxysporum*	Rice	In vitro	[67]
Ag NPs	Green method by using Malia azedarach	Spherical, 23 nm	*Verticillium dahliae*	Potatoes	In vitro and in vivo	[68]

Table 1 (continued)

Types of NPs	Method of synthesis	Characterization (shape and size)	Fungus specie	Targeted crop	Evaluation method	References
Ag NPs	Green synthesis by Pachira glabra	Spherical, 29	*Rhizopus nigricans*	Peach	In vitro	[69]
Ag NPs	Green synthesis by Proteus vulgaris	Spherical, 12–16 nm	*Fusarium oxysporum, Fusarium acuminatum, Fusarium tricinctum*	Barley	In vitro	[70]
Ag NPs	Green synthesis by rice leaf	Spherical, 3.7–29.3	*Rhizoctonia solani*	Corn	In vitro	[71]
TiO_2 NPs	Green synthesis by Trianthema portulacastrum, Chenopodium quinoae	Cluster form, 15 nm	*Ustilago tritici*	Wheat	In vivo	[72]
Ag NPs	Green synthesis by Phyllanthus urinaria, Plumbago zeylanica	Various morphologies, 4-53 nm	*Aspergillus niger, Aspergillus flavus, Fusarium oxysporum*	Wheat	In vitro	[73]
TiO_2 NPs	Biological method	–	*Candida albicans*	Cereals, legumes	In vivo	[74]
Ag NPs	Green synthesis by Bacillus pseudomycoides	Spherical, 25–43	*Aspergillus flavus, Aspergillus niger, Penicillium chrysogenum*	Barley	In vitro	[75]
Ag NPs	Green synthesis by sodium alginate	Spherical, 6–40	*Colletotrichum gloeosporioides*	Corn	In vitro	[76]
Cu NPs	Green Synthesis by ascorbic acid	Faceted, 200–500	*Fusarium solani, Fusarium oxysporum*	Maize	In vitro	[77]
Cu NPs	Ascorbic acid	Spherical, 53–174	*Fusarium oxysporum, Phytophthora capsici*	Rai	In vitro	[78]
CeO NPs	Green synthesis by *Acorus calamusas*	Spherical, 42 nm	*Puccinia striiformis*	Maize, wheat, rice	In vivo	[79]
Ag NPs	Green synthesis by Withania somnifera	Spherical, 10–21 nm	*Fusarium solani*	Prickly pear, date palm	In vitro. In vivo	[80]
Ag NPs	Green synthesis by green and black teas	Spherical, 10–20 nm	*Aspergillus flavus, Aspergillus parasiticus*	Maize	In vitro	[81]
Ag NPs	Green Synthesis by Tropaeolum majus	Spherical, 35–55	*Aspergillus niger, Penicillium chrysogenum, Trichoderma viride*	Maize	In vitro	[82]
Ag NPs	Green Synthesis by Trichoderma longibrachiatum	Spherical, 10	*Fusarium verticillioides, Fusarium moniliforme, Penicillium brevicompactum*	Wheat	In vitro	[83]
Ag NPs	Green Synthesis by Fusarium oxysporum	Spherical, 10–30	*Pythium aphanidermatum*	Wheat	In vitro	[84]
Cu NPs	Green Synthesis by Streptomyces capillispiralis	Spherical, 3.6–59	*A. foetidus, Aspergillus flavus, Aspergillus niger*	wheat	In vitro	[64]
Ag NPs	Green synthesis by Streptacidiphilus griseoplanus	Spherical, 19.5–20.9	*Macrophomina phaseolina*	Maize	In vitro	[85]

Table 1 (continued)

Types of NPs	Method of synthesis	Characterization (shape and size)	Fungus specie	Targeted crop	Evaluation method	References
Cu NPs	Green Synthesis by Persea americana	Spherical, 42–90	*Aspergillus flavus, Aspergillus fumigatus and Fusarium oxysporum*	Wheat	In vitro	[86]
Cu NPs	Green Synthesis by green and black teas	Spherical, 26–40	*Penicillium chrysogenum and Aspergillus flavus*	Corn	In vitro	[81]
Ag NPs	Green synthesis by Osmanthus fragrans	Spherical, 20	*Bipolaris maydis*	Maize, wheat	In vitro	[87]
Ag NPs	Green synthesis by Satureja hortensis L		*Fusarium oxysporum*	Tomato, eggplant and pepper	In vitro	[88]
Ag NPs	Green synthesis by Osmanthus fragrans	Spherical, 20	*Bipolaris maydis*	Corn leaf	In vitro	[87]
Ag NPs	Green Synthesis by ajwain and neem	68	*Colletotrichum musae*	Rai	In vitro, in vivo	[89]
Ag NPs	Green synthesis by Tagetes patula	Spherical 15–30 nm	*Chlorophyte Ore*	Corn	In vitro, in vivo	[90]
Ag NPs	Green synthesis by Amaranthus retroflexus	Spherical, 10–32 nm	*Macrophomina phaseolina, Alternaria alternata, Fusarium oxysporum*	Barley	In vitro	[91]
Ag NPs	Green synthesis by Chaetomium globosum	Spherical, 11 and 14	*Fusarium oxysporum*	Corn	In vivo and in vitro	[92]
Ag NPs	Green synthesis by Zingiber officinale	Spherical, 75.3	*Alternaria alternata, Cochliobolus lunatus*	Wheat	In vitro	[93]
Ag NPs	Green synthesis by Trichoderma viride	Spherical, 12.7	*Alternaria solani*	Wheat	In vitro	[94]
Ag NPs	Green synthesis by Cryptococcus laurentii, Rhodotorula glutinis	Spherical, 15–400	*Botrytis cinerea, Penicillium expansum, Aspergillus niger*	Maize	In vitro	[95]
Ag NPs	Green synthesis by Aspergillus versicolor	Spherical, 5–30	*Sclerotinia sclerotiorum and Botrytis cinerea*	Wheat	In vitro	[96]
Ag NPs	Green synthesis by Althaea officinalis, Mentha pulegium	Spherical, 50 nm	*Aspergillus flavus, Penicillium chrysogenum*	Maize, wheat, rice barley	In vitro	[97]
Ag NPs	Green synthesis by Electron shell	Spherical and oval, 10–50 nm	*Phytophthora infestans, Phytophthora capsici*	Wheat	In vitro	[98]
Ag NPs	Green synthesis by Fusarium solani	Spherical, 5–30	*Fusarium oxysporum, Fusarium solani, Fusarium moniliforme*	Rai	In vitro	[99]
Ag NPs	Green synthesis by Bacillus subtilis	Spherical, 16–20	*Aspergillus niger, Aspergillus nidulans, Cladosporium herbarum*	Corn	In vitro	[100]

Table 1 (continued)

Types of NPs	Method of synthesis	Characterization (shape and size)	Fungus specie	Targeted crop	Evaluation method	References
Ag NPs	Green synthesis by Aspergillus terreus	Spherical, 5–30	*Aspergillus flavus*	Rai	In vitro	[101]
Ag NPs	Green Synthesis by Trichoderma longibrachiatum	Spherical, 1–20	*Fusarium oxysporum*	Maize	In vitro	[102]
Ag NPs	Green synthesis by Aspergillus foetidus	Spherical, 20–40	*A. foetidus, Aspergillus flavus, Aspergillus niger*	Rai	In vitro	[103]
Ag NPs	Green synthesis by Azadirachta indica	Spherical, 10–50 nm	*A. alternata, Sclerotinia sclerotiorum, M. phaseolina, R. solani, B. cinerea, and C. lunata*	Maize sorghum, millet, wheat	In vitro	[49]
Ag NPs	Green synthesis by glucose	Spherical, 5–24	*Colletotrichum gloeosporioides*	Rai	In vitro	[104]
Cu NPs	Green synthesis by ascorbic acid	Faceted, 200–501	*Fusarium oxysporum and f.sp. Lycopersici*	Barley	In vitro and in vivo	[105]

excerpts of *Moringa oleifera* [115]. These green nanoparticles have also an effective antifungal agent when mixed with GNPs [116]. GNPs were found more effective when used with suitable non-toxic reducing agents, especially sodium boro-hydride and sodium citrate, respectively [117]. According to Mittal et al. a range of stabilizing and reducing agents for the management of fungal infections in agriculture may be made from plants [118]. Therefore, to prevent fungal illnesses, non-toxic, healthful, and environmentally friendly sources must be developed [119, 120]. Fungicides made of synthetic chemicals are poisonous and harmful to the environment, soil biodiversity, and human health. Accordingly, trends are changing in favor of using NPs to safely and effectively treat fungal infections in plants. It has been discovered that organic and inorganic NPs with a variety of biological purposes are effective against bacterial, viral, and fungal infections. Plant extracts are the most significant biological material bio-reductant for the creation of NPs [121]. Since phyto-extracts control fungal infections, encourage plant development, and successfully lower agricultural illnesses, they may be utilized to synthesize environmentally friendly NPs [122]. It is discovered that the several "green" produced NPs are lucrative, non-toxic, easy to use, and inexpensive. They are appropriate for curing agricultural plants of diseases. Compared to the several old approaches, the green synthesis using NPs produced more stable synthesized materials and is an essential component of agricultural sustainability [123].

Green nanoparticle manufacturing and use are likely to increase due to rising environmental consciousness, regulatory pressure to eliminate hazardous waste, and demand for sustainable solutions. The three categories of green nanoparticle synthesis are phytochemicals, extracellular, and intracellular. Due to the availability of phytochemical components in the extract, which can also function as reducing and stabilizing agents to turn metal ions into metal nanoparticles, the process of producing metal nanoparticles from plant extract is low cost and high yield [124]. Green nanoparticles, a fast-expanding sector, are experiencing substantial development due to increased demand for sustainable solutions across a variety of sectors. Global green nanotechnology market, estimated to increase from 2020, is expected to grow more by 2030, with high contributions from various countries of the world. The consumption and production of green NPs synthesized by eco-friendly methods are growing rapidly, as industries seek sustainable alternatives for their businesses. Green nanotechnology global market, estimated valued at $8.3 billion in 2020, will be projected to reach $26 billion till 2028, with significant contributions from the Asia-Pacific region. The main contributions of green NPs are mainly used in environmental remediation, agriculture, medicine, and with the healthcare sector driving substantial growth [125–127]. Environmental and agricultural applications are also expanding and reflect huge demands for sustainable solutions across these industries.

The global commercial production of green NPs faces challenges in scaling up despite growing interest in sustainable synthesis methods. Plant-based green synthesis has been proposed as an alternative, it has yet to achieve large-scale commercial viability [128]. Green nanoparticles are rapidly being employed in health, agriculture, and environmental remediation, with considerable market growth predicted in these sectors. Nanoparticles are found in both organic and inorganic modules, including ferritins, liposomes, micelles, dendrimers, and magnetic NPs, as well as metal and semiconductor NPs such as oxides, nitrides, and sulfides [129]. These green nanoparticles are sprayed as foliar treatments to the targeted crops to reduce disease. Overall, nanoparticle-based treatments are potential alternatives to traditional fungicides for controlling plant diseases in a variety of crops [130].

Antifungal activity of other nanocomposites synthesized by conventional methods

The overuse of pesticides and other chemicals, along with conventional methods for nanoparticle synthesis, has detrimental impacts on soil fertility, soil microorganisms, and the health of people, plants, and animals. By altering metabolic and physiological processes, the increasing use of conventional fertilizers has led to the emergence of pathogen strains that are resistant to them and delays the growth of photosynthetic pigments and plant reproductive organs. They also prevent plants from going through mitosis, forming microtubules, and respiring their cells. Engineered nanoparticles exhibit promise antifungal effectiveness against a variety of fungal species, including drug-resistant Candida albicans. Silver nanoparticles (Ag-NPs) have considerable antifungal activity, equivalent to traditional antifungal treatments [131]. Polyvinylpyrrolidone-coated Ag-NPs, when coupled with azole antifungals, have synergistic effects on resistant *C. albicans*, compromising cell membrane integrity and preventing budding processes. Amphotericin B-conjugated silica nanoparticles have fungicidal action against Candida sp. and may be reused repeatedly without losing efficacy [132]. Sub-lethal doses of different nanoparticles, such as Ag, SiO_2, TiO_2, and ZnO, might improve the antifungal activity of beneficial bacteria such as Pseudomonas protegens CHA0 by increasing the formation of antifungal chemicals [133]. These findings indicate that tailored nanoparticles may have significant benefits in fighting fungal infections and developing novel antifungal strategies. The research with carbon-nano tubes (CNTs) verified that multi-walled-carbon nanotubes (MWCNTs) can greatly enhances both the ability of seed germination and plant growth by control of antifungal activities. Furthermore, Tripathi and Sarkar [41] found that applying water-soluble CNTs helped wheat plants expand their roots and shoots in both light and dark environments. Additionally, it has been confirmed that industrial-grade MWCNTs (2560 mg kg^{-1}) significantly increased crop germination and root elongation [42]. The following Table 2 explores the antifungal/antimicrobial action of various other nanomaterials that are being applied for antifungal activities on different crops.

Mechanism involved in the antifungal activity of green nanoparticles

Applying nanoparticles as a foliar spray on the cereal crops provide a multifaceted approach to fighting fungal infections, leveraging both direct antifungal properties and indirect benefits through soil and plant health improvement. When cells were exposed to NPs, they produced more ROS and OH radicals, reducing regulation of antioxidant machinery and oxidative enzymes, disrupting cellular integrity and osmotic balance, and decreasing pathogenicity. As a result, lipid peroxidation increased, inflammation developed, mitochondrial function declined, and cell death succeeded [141, 142]. There was evidence that NPs caused cell death by a caspase-dependent pathway, suggesting they could induce apoptosis. As a result of NPs, ROS were generated more and antioxidant enzyme activity decreased. Antifungal effects of metallic nanoparticles are attributed to their electropositive surfaces, which oxidize plasma membranes and allow entry into the pathogen body [142–144]. The results of Zhang [145] provide more evidence for this, since they address the reversible conversion of Ce (III)/Ce (IV) between two valence states as a unique antibacterial mechanism. The role of ROS in the antibacterial activity of CeO_2 NPs is also highlighted by Kuang et al. [146] who found that exposure to these particles can increase intracellular ROS levels in *E. coli*. However, the specific mechanism of the antifungal activity of CeO_2 NPs and biochar is not fully elucidated and requires further research. It is possible that ROS generated by CeO_2 NPs are involved in the disruption of cell walls, leading to the death of fungal cells. It is also likely that ROS can activate the immune system, aiding in the fight against fungal infections. ROS may also damage the fungal membrane, preventing the transport of essential molecules such as oxygen and nutrients. Additionally, ROS can react with fungal enzymes, damaging their ability to catalyze important reactions. ROS can also damage the DNA of fungal cells, leading to mutations that prevent the cells from reproducing and spreading. Furthermore, in one of its foliar applications to wheat seedlings, ZnO NPs of nAl_2O3 (< 50 nm) shown reducing the root length of the plants owing to oxidative stress activity of superoxide dismutase with catalase enzymes raising. The smaller concentration of ZnO NPs causes healthy impact on seed germination process. On the contrary, higher concentration of ZnO NPs can cause seed germination degradation as it is insoluble in water. The ZnO NPs display antifungal effects by inducing oxidative stress and damaging fungal cell membranes. Additionally, ZnO NPs created using phyto-extract of Eucalyptus beads were investigated to predict the fungal pathogen that causes illness in apple plants. Amazingly at 100 ppm concentrations, the highest reserve of 76.3% was noticed for pathogen *Alternaria mali*, 65.4% for *Botryosphaeria dothidea* and 55.2% for *Diplodia seriata*, respectively. Thus, it is possible to use these NPs to effectively control the aforementioned fungal infections in order to safeguard different fruit harvests in agriculture on time [74]. The silver-based chitosan Ag-Chit NPs possess antifungal properties due to their ability to bind to fungal cell walls, disrupting their body structure. They are found very fruitful, especially in its role as bio-fungicides in the field of agriculture. The Ag-Chit NPs were proved very effective in controlling the fungicides and pest communities of *A. flavus* present in the feed of livestock. These pest-suffered feed samples were collected and accordingly treated by Ag-Chit NPs composites of 30, 60 and 90 mg, respectively, for 10 days incubation at 10 °C producing successful results. Animal pests can cause agricultural harvests to drop by up to 18%, while microbiological illnesses and weeds caused losses of 16% and 34%, respectively. Fungal infections have been responsible for agricultural losses exceeding 200 billion euros annually [147]. Figure 3 provides the insightful mechanism against the fungus pathogen of wheat crop under the combined application of nano-biochar. Nanoparticles significantly increased the permeability of cells when exposed to them, resulting in alterations to their membranes.

Toxicological effects of green nanoparticles

Green nanoparticles' hazardous behavior toward the environment and its constituent parts has not been well examined. Nonetheless, a lot of research has been done on the harmful effects of the physicochemical characteristics of artificial nanoparticles. It has been discovered that the oxidation potential, DNA damaging potential, and pharmacological behavior of smaller particles are directly correlated. Almost all cell types are harmful to particles smaller than 50 nm [148]. According to Tran et al. [149], these green nanoparticles have the ability to stay suspended in water and the air for extended periods

Table 2 Antifungal activities of various other nanocomposites

Type of nanocomposites	Synthesis route	Working conditions	Applied technique	Microbe studied	Outcomes	References
Ag NPS-titanate nanotubes	Hydrothermal microwave synthesis of Ag NPs and titanate nanotubes	30 mg/30 mL	In vitro study of photo-activated Ag NPs titanate nanotubes	*Botrytis cinerea*	ROS damage causes the fungal cell death	[134]
ZnO\\Fe_3O_4/AgBr	Synthesis through microwave-assisted physical method	1:8 mg/ mL	In vitro spore broth incubation study	*Fusarium graminearum, Fusarium oxysporum*	Death of fungus cells in one hour	[135]
Au/Ag combined with ZnO NPs	Physical method	50:10 µg/mL	In vitro study using Sabouraud dextrose agar (SDA) medium	*Aspergillus flavus/A. fumigatus*	Augmented inhibition of fungal growth by bimetallic and metal oxide NPs	[136]
Composite of ZnO:$Mg(OH)_2$	Co-precipitation technique by hydrothermal synthesis	0.002 to 5 mg/mL	In Vitro study involving Dimethyl Sulfoxide dissolved (DMSO) with NPs	*Colletotrichum gloeosporioides*	MgO and ZnO NPs proven to be good antifungal agent	[137]
CuO NPs and carbon composite	Green synthesis using *Adhatoda vasica* leaf extract and $CuSO_4$ solution	5:4 (leaf extract: $CuSO_4$)	In vitro using potato dextrose (PDA) medium	*Candida albicans, Aspergillus niger,*	Cell death occurred due to disruption of the cell membranes	[138]
Cu-/Zn chitosan bimetallic nanocomposites	Chemical synthesis via wet deposition	(30, 60, 100) µg/mL	Study using agar based media for seed priming in cotton cultivar Giza 92	*Rhizoctonia solani*	Inhibition of fungus cell at the tested doses	[139]
Clay-chitosan nano-composite	Anion-exchange technique	(5–60) µg/mL	In vitro study using PDA medium and In vivo essay in *Citrus sinesis (L. Osbeck)*	*Penicillium digitatum*	Fungal hyphae are completely inhibited by clay/chitosan nano-composite (1:0.5, 1:1, 1:2) (conc. 20 µg/mL)	[140]

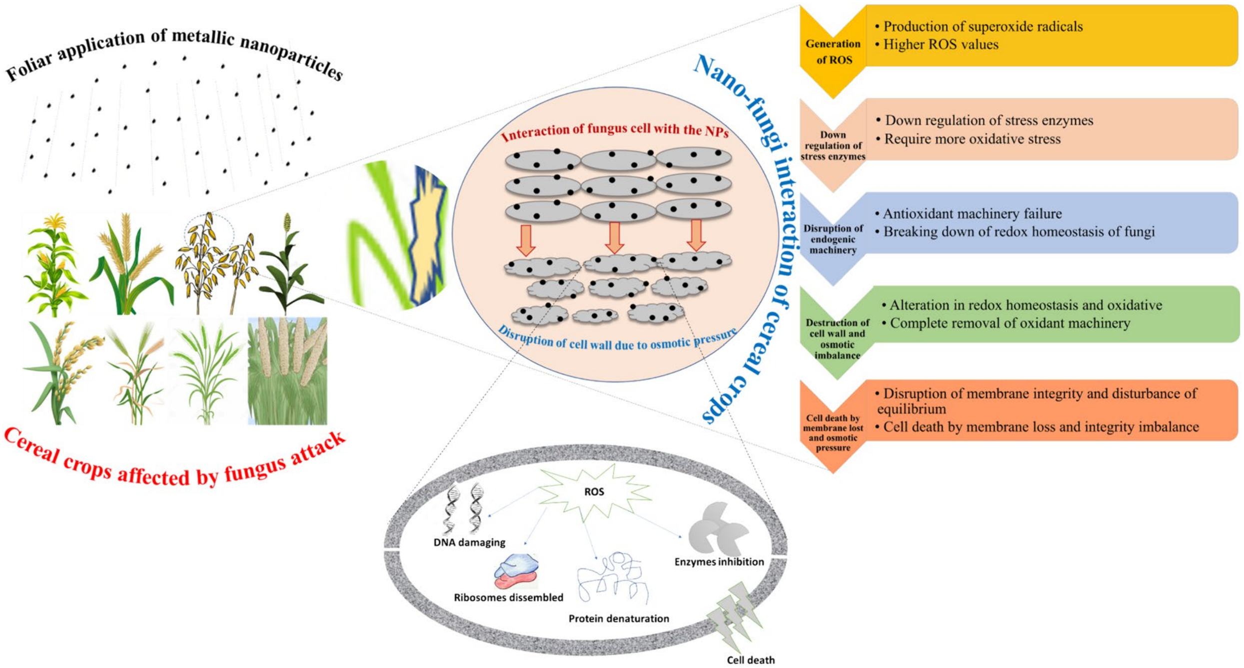


Fig. 3 Mechanism of antifungal activities of green nanoparticles

of time, exposing living things for longer and increasing their toxicity. According to reports, endocytosis and phagocytosis are influenced by the nanoparticle's form (triangular, star, tubular, or circular) [150]. It was also discovered that endocytosing circularly shaped nanoparticles was simple and they could be endocytosed quickly and efficiently even in the presence of other nanoparticles [151]. According to Gatoo et al. [150], a particle's surface charge has a significant influence on its agglomeration behavior and, consequently, its toxicity may increase. Furthermore, surface coatings of organic compounds can affect the pore structure, surface charge, surface roughness, reactivity, and surface roughness of green nanoparticles, depending on the type of coating. The performance of green nanoparticles in a range of applications, such as biomedical, energy, and materials, can be strongly impacted by these features. Therefore, before green nanoparticles are applied, designed, or developed, their toxicological effects should be taken into account.

Emerging trends and technologies in agriculture sector

Emerging trends and technologies in agricultural arena make use of state-of-art data-driven decision-making through latest sensors and drones for fastidious farming based on green nanotechnology. In the future, farms will be factories to meet consumer needs. With the rise of capital-intensive industries and services, artificial intelligence (AI), robotics, and machine learning are replacing humans, saving them labor. The largest obstacle facing emerging nations is the lack of well-paying jobs in the agricultural sector, including secondary agriculture, processing, packaging, value chains, and value addition. Bio-based goods are finding increasing applications in the fields of alternative energy, building materials, chemicals, polymers, pharmaceuticals, cosmetics, fertilizers, nutrition, and insect/pest control. Biofuels are made from grains, oilseeds, and sugarcane [152]. Promotion of novel CRISPR–Cas9 and other gene editing tools can aid in the development of genetically engineered crops with increased resistance and nutrient value. The development of controlled-environment agriculture through the use of vertical farming (VF) is one of the finest strategies for ensuring year-round output with lower resource consumption, particularly in urban agriculture. The widespread adoption of GNT may improve global sustainable development, and the inclusion of a block-chain system for transparent supply chains can secure the agricultural requirements of both current and future generations [153, 154]. At the same time, the GNT innovations mutually boost the energy efficiency, food sustainability by maintaining a fair balance between environmental resources, economy and social needs of the people as per the United Nations Sustainable Development Goals (SDGs). Despite having few commercially available products, green nanotechnology is still primarily in the research and development stage, despite its potential for sustainability and environmental benefits. Even though it claims to cut hazardous waste, greenhouse gas emissions, and energy consumption, its current influence on environmental protection is negligible. However, due to their special qualities, nanomaterials are useful for lowering environmental risks, improving energy efficiency, and producing long-lasting, environmentally friendly products. These technologies are anticipated to contribute significantly to energy challenges and climate change mitigation as they develop.

Conclusion

In order to address the present challenges of global warming, overconsumption of natural resources, and an ever-rising population, there is need of shifting from unsustainable traditional agricultural practices, causing the growth of chemical fungicides to eco-friendlier practices for ensuring global food security. The promotion of green nanotechnology is a suitable option for sustainable management of various plant pathogens without affecting the environment. This critical review profoundly calls for the large-scale production and use of green nanoparticles synthesized by plant extracts, which can greatly enhance the quality and yields of food by curtailing the harmful effects of chemicals and fungicides in the field of present-day agriculture. Green nanotechnology should be encouraged at large-scale due to its cost-effectiveness and environment friendly properties and its ability to ensure sustainable global food supplies to achieve some of the United Nations Sustainable Development Goals.

Futuristic scope and prospective of green nanotechnology for antifungal activity

Certain concern needs to be addressed before the large-scale application of nanotechnology practices in agriculture sector. For instance, the antifungal management requires nano-hybrid materials which are merged by various combinations of gold, silver, zinc, grapheme, copper, iron, polymers say chitosan and variety of organic molecules and chemicals which are highly expensive. At the same time the nano-hybrid construction techniques require expensive high-tech devices of higher energy inputs needs can raise the production cost of nano-hybrid materials. The use of nanohybrids is mostly very effective against phytopathogens control but in actual field conditions, they sometime display off-target movements and may damage the plants by entering into the vegetative parts of the plants.

Hence, the potential impacts of various nanoparticles for antimicrobial and fungicidal applications must be fully registered before evolving the particular nano-formulations and nanohybrids for agriculture purposes. It is also noticed that most metallic/metal oxide NPs may exercise negative impacts in plants and can also alter or reduce the soil microbial levels. Marketing of GNT products is another sky-high issue for their field use on broader levels possibly due to multifarious reasons including unclear technical benefits, high cost, lack of formers/public awareness and uncertainties in legislation about GNTs. Due to these reasons the applications of GNTs in agriculture sector is minimal as compared to other sectors of social and natural sciences. The sensors/kits built of nanomaterials should be used throughout the post-harvest phase in order to promptly identify the fungal infection. The concentration of nanocomposites used in a field determines how harmful they are. When compared to the concentrations of chemical-based insecticides and fungicides, the working concentrations of nanocomposites are relatively low. The capacity of biodegradable polymers to easily translocate inside plant tissues and to have antifungal properties in plants is the ultimate goal when creating nano-composite materials using different combinations of metal and metal oxide nanoparticles. Therefore, further research on biodegradable polymers should be encouraged due to their eco-friendly and biocompatible nature, which ensures sustained formation. The time, money, and resources required to produce GNT for agriculture can be recovered by establishing biological synthesis techniques. Additionally, it may successfully reduce the quantities of environmentally hazardous chemicals needed for the commercial synthesis of non-composite materials and nanomaterials using the most well-researched physical/chemical synthesis methods accessible worldwide.

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Author contributions

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Availability of data and materials

All the data of this study is contained in the manuscript. For any additional data or information needed regarding this review article, please contact the corresponding authors.

Declarations

Competing interests

The authors declare no competing interests.

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