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Green Nanotechnology: Plant-Derived Nanoparticles for Sustainable Agriculture and Environmental Restoration

Saumya Agrawal[1,2], Mohit Gururani[1], Rajat malik[1], and Kusuma Kumari Panda[1*]

[1]Amity Institute of Biotechnology, Amity University, Sector 125, Noida, Uttar Pradesh, India
[2]Department of Biological Sciences BITS- Pilani, K.K. Birla Goa campus, Zuarinagar, Goa, India
*Corresponding author: Email ID: pkkumari@amity.edu

Abstract

Nanotechnology presents transformative solutions to global agricultural and environmental concerns, with plant-derived nanoparticles emerging as sustainable and long-lasting alternatives to chemically generated counterparts. This review explores the synthesis, characteristics, and numerous applications of green nanoparticles, with a special emphasis on their role in different aspects of life. Green nanoparticles, which are generated from plants, fungi , and other biological systems, have distinct catalytic, electrical, and thermal properties, making them particularly successful in sectors such as biomedicine, agriculture, and environmental sciences. Plant-derived nanoparticles in agriculture foster crop development, reduce abiotic stress, and elevate disease resistance, lowering the need for toxic chemical pesticides and fertilizers. Nanofertilizers and nanobiopesticides provide precision distribution while reducing chemical residues and boosting environmental sustainability. Moreover, these nanoparticles assist in environmental rehabilitation, displaying the ability to absorb heavy metals and organic contaminants from water and thereby restore polluted ecosystems. This article emphasizes the increasing interest in biologically manufactured nanoparticles due to their environmental accessibility, cost-effectiveness and compliance with sustainable practices while acknowledging the issues with scalability of green synthesis, nanoparticle toxicity and long-term consequences. It concludes by discussing the future research objectives and broader implications of green nanotechnology in resolving global issues.

Keywords: Plant-derived Nanoparticles; Nanobiopesticides; Nanofertilizers; Nanobioremediation; Agriculture application

1. Introduction

Nanoparticles are structures or molecules ranging from 1 and 100 nm with various applications in the field of chemistry, physics, biology, medicine, engineering and electronics. The study of nanoparticles, known as nanoscience, is a new and emerging technology of the 21st century driving new investigations, development of innovative devices and solutions [1]. Nanoparticles can be natural or manufactured, either in an unbound state or as an aggregate. Nanoscience plays a pivotal role in advancing nanotechnology by enabling the manipulation of materials at the atomic and molecular levels, resulting in novel devices and systems with tailored physical and chemical properties. Nanoparticles can be classified on parameters such as based on dimension, or composition [2,3].

Nanomaterials have unique physical properties such as catalytic, electrical, mechanical, magnetic, imaging, or thermal qualities, making them suitable for a variety of applications [2].Advanced microscopic techniques such as Scanning electron microscopy (SEM), transmission electron microscopy (TEM) and atomic force microscopy (AFM) are employed for characterization of nanoparticles based on attributes like size, surface area, composition, surface morphology, surface charge,

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10.5530/ctbp.2025.3s.3

crystallographic structure and concentration [3,4].

Nanoparticles can be produced using both chemical and biological processes. Recent research has demonstrated that chemically produced nanoparticles can have negative consequences due to the presence of toxic chemicals adsorbed on their surfaces[5] To address the growing demand for non-toxic and environmentally-friendly nanoparticles, researchers have developed “green” approaches for the synthesis of such cost-effective, and safe nanoparticles in recent years. Green approach towards production of nanoparticles includes several biological systems such as yeast *(Saccharomyces cerevisiae)*, fungus, bacteria, and plants. Among these systems, plant derived nanoparticles stand out for their diversity, ease of use and scalability. Examples of these include silver, gold, zinc-oxide, copper, nickel, and manganese [4,6].

Recently, diverse applications of nanoparticles have been investigated along with strategies to implement them into plant and animal systems. Despite certain challenges, promising approaches are being explored to overcome limitations and harness their full potential.

Nanoparticles have shown immense potential in various fields, including biomedicine, pharmaceuticals, physicochemical processes, drug delivery, disease management, and environmental remediation (nanoremediation) [7,8]. While certain applications of nanoparticles have been previously reviewed, here we provide an update on recent advances in applications of biologically synthesized nanoparticles. This paper highlights their key features, future prospects for their development and the challenges that need to be addressed for the continued improvement in this field of research.

2. Types of Nanoparticles

The nanoparticles can be classified into several types based on their sources, extraction methods and applications (Table 1). Every nanoparticle possesses a different property and behaves differently when subjected to similar environmental conditions. For example, starch-based nanoparticles are biodegradable and thus have a set applicability and fixed expiration duration, whereas metal-based nanoparticles are not biodegradable and tend to stay in the environment for longer periods of time. This difference is one of several that enables the researchers to apply nanoparticles in various settings in a laboratory, ranging from biodegradation to cancer drug delivery. Today several nanoparticles are available for use in daily laboratory settings with some of them being highly specialized and some being for general purposes. Ultimately, what nanoparticle is employed boils down to the purpose it needs to serve in a given environment.

Figure 1 illustrates the classification of nanoparticles into three main categories i.e. metallic, organic and metal oxide. Metallic nanoparticles are composed of metals such as gold, silver, or platinum, organic nanoparticles are made from organic materials like lipids, polymers, or carbon-based compounds and metal oxide nanoparticles are derived from metal oxides such as titanium dioxide, zinc oxide, or iron oxide.

3. Nanoparticles in Growth and Development/Stress Tolerance

Plants encounter several abiotic stressors such as extreme temperature, drought, salinity, heavy-metal toxicity and floods depleting its growth and development. [36]states that 51-82% of crop productivity is depleted due to abiotic stresses every year. The use of chemical pesticides and synthetic products for improving crop productivity pose harm to the agricultural ecosystem. In contrast, nanotechnology used to synthesize green-NPs can mitigate issues of nutrient deficiency, stress susceptibility, oxidative stress and reactive oxygen species (ROS) [37].Under heat, salinity, heavy metal poisoning or cold conditions, plant defense mechanism produces excess ROS causing oxidative stress leading to changes in molecules such as DNA, proteins,

Vol. 19 (Supplementry Issue 3A), September 2025, ISSN 0973-8916 (Print)., 2230-7303 (Online)
10.5530/ctbp.2025.3s.3

Table 1: Types of nanoparticles currently available along with their sources and commercial applications

Type	Source	Applications	References
Nanocellulose	plant cellulose, commonly from wood, cotton, or another biomass.	Used to adsorb heavy metals (e.g., lead, mercury, cadmium) and organic pollutants (e.g., dyes, pesticides) from water.	[9]
Zein Nanoparticles	*Zea Mays* (corn protein)	Zein-based nanoparticles are utilized to remove organic pollutants like dyes from wastewater.	[10]
Pectin Nanoparticles	Extracted from fruits like apples and citrus peels.	Pectin-based nanoparticles are effective in adsorbing heavy metals from aqueous solutions.	[11]
Plant Extract Synthesized Metal Nanoparticles	Plant extracts like *Azadirachta indica, Camellia sinensis, Aloe barbadensis miller*, and others are used to synthesize metallic nanoparticles (e.g., silver, gold, iron, zinc) through green synthesis methods.	These nanoparticles are used for the degradation of organic pollutants, reduction of toxic heavy metals, and disinfection of microbial contamination in water and soil.	[12]
Lignin Nanoparticles	Derived from lignin, a natural polymer found in wood and plant cell walls.	Lignin nanoparticles can be used to adsorb heavy metals, organic pollutants, and dyes from wastewater.	[13]
Starch Based Nanoparticles	Derived from starch, typically from corn, potatoes, or other starch rich plants.	Used to remove heavy metals like lead and copper, as well as organic pollutants from aqueous systems.	[14]
Chitosan Nanoparticles	Chitosan can be derived from plant sources such as fungi.	Chitosan nanoparticles are used to remove heavy metals, dyes, and other organic pollutants from wastewater due to their strong chelating properties.	[15]
Curcumin Nanoparticles	Curcumin is extracted from turmeric *(Curcuma longa)*.	Curcumin nanoparticles are used for the degradation of organic pollutants such as dyes and pharmaceutical wastes due to their antioxidant and catalytic properties.	[16]
Tannic Acid Coated Nanoparticles	Tannic acid is extracted from plants such as oak, tea, and chestnuts.	Tannic acid coated nanoparticles are used to remove heavy metals and dyes from water.	[17]

Vol. 19 (Supplementry Issue 3A), September 2025, ISSN 0973-8916 (Print)., 2230-7303 (Online)
10.5530/ctbp.2025.3s.3

Aloe Vera Synthesized Nanoparticles	*Aloe barbadensis miller* plant extract.	Aloe vera is used to synthesize nanoparticles like silver (Ag) and iron (Fe), which are applied in the remediation of wastewater.	[18]
Citrus-Peel Extract Nanoparticles	Orange, lemon, and other citrus fruits.	Citrus peel extract is used to synthesize metal nanoparticles (e.g., silver, gold), which are employed for the removal of dyes, heavy metals, and microbial contaminants from water.	[19]
Neem Extract Synthesized Nanoparticles	Neem *(Azadirachta indica)* extract.	Neem extract is used to synthesize metal nanoparticles, particularly silver nanoparticles, which have been effective in degrading organic pollutants and reducing heavy metal toxicity in contaminated environments.	[20]
Silver Nanoparticles	*Azadirachta indica* (Neem); *Camellia sinensis* (Green Tea); *Allium sativum* (Garlic); *Ocimum sanctum* (Tulsi)	Antibacterial, antifungal, antiviral, wound healing, biomedical devices	[21]
Gold Nanoparticles	*Magnolia kobus; Azadirachta indica (Neem); Pelargonium graveolens (Geranium); Mentha piperita (Peppermint)*	Drug delivery, cancer therapy, imaging, diagnostics.	[22]
Copper Nanoparticles	*Punica granatum* (Pomegranate); *Moringa oleifera; Lantana camara*	Antimicrobial agents, catalysts, conductive inks, sensors	[23]
Zinc-Oxide Nanoparticles	*Aloe barbadensis miller* (Aloe vera); *Calotropis gigantea* (Crown flower); *Acalypha indica*	Sunscreens, antimicrobial agents, optical devices, photocatalysts.	[24]
Iron Oxide Nanoparticles	Tea leaves; Aloe vera; Eucalyptus globulus	Magnetic resonance imaging (MRI), drug delivery, environmental remediation.	[25]
Platinum Nanoparticles	*Cymbopogon citratus*(Lemongrass); *Terminalia arjuna; Abelmoschus esculentus* (Okra)	Catalysis, cancer treatment, fuel cells.	[26]
Titanium Dioxide Nanoparticles	*Trigonella foenumgraecum* (Fenugreek); *Psidium guajava* (Guava); *Ecliptaprostrata*	Sunscreens, photocatalysts, environmental purification, antibacterial agents.	[27]

Vol. 19 (Supplementry Issue 3A), September 2025, ISSN 0973-8916 (Print)., 2230-7303 (Online)
10.5530/ctbp.2025.3s.3

Palladium Nanoparticles	*Coriandrum sativum* (Coriander); *Catharanthus roseus* (Periwinkle); *Cinnamomum camphora* (Camphor tree)	Catalysts, hydrogen storage, organic reactions, electronics	[28]
Selenium Nanoparticles	*Zingiber officinale* (Ginger); *Allium cepa* (Onion); *Withania somnifera* (Ashwagandha)	Antioxidants, cancer therapy, antimicrobial agents	[29,30]
Nickel Nanoparticles	*Eucalyptus globulus; Cymbopogon flexuosus (Lemongrass); Lippianodiflora (Frog fruit)*	Catalysis, sensors, energy storage devices, magnetic materials.	[31]
Magnesium Oxide Nanoparticles	*Lagerstroemia speciosa; Eucalyptus globulus; Ocimum sanctum (Holy Basil)*	Antimicrobial agents, flame retardants, environmental remediation.	[32]
Cadmium Sulfide Nanoparticles	*Ocimum basilicum*(Basil); *Aloe barbadensis miller* (Aloe vera); *Azadirachta indica* (Neem)	Photovoltaic cells, sensors, optoelectronics.	[33]
Bismuth Nanoparticles	*Eucalyptus globulus; Piper nigrum (Black Pepper); Ocimum sanctum (Tulsi)*	Radiopharmaceuticals, imaging, cancer therapy.	[34]
Cobalt Nanoparticles	*Magnolia kobus; Rosmarinus officinalis (Rosemary); Camellia sinensis (Green Tea)*	Catalysis, magnetic storage media, biomedical applications.	[35]

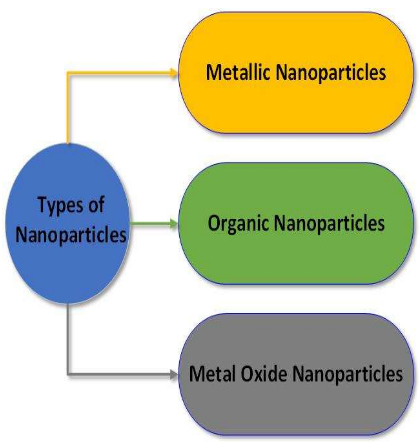

Fig. 1: Illustration of classification of nanoparticles into three major categories (Metallic Nanoparticles, Organic Nanoparticles, Metal Oxide Nanoparticles).

lipids, which in turn disrupts biological processes of stomatal closure, CO_2 intake, photosynthesis and many more [38].

To reduce ROS production, [39]used titanium dioxide nanoparticles (TiO_2NP) from aloe vera on two varieties of soybean and observed reduced ROS production under stress conditions[40]. Similarly, [41]used TiO_2NP synthesized from *Buddleja asiatica* plant extract on wheat under salinity stress and noticed improved osmotic and water potential as well as enhanced osmolytes accumulation such as total phenolics, flavonoid content, proline and amino acid content along with increased antioxidant activity. In another study, Silicon nanoparticles (SiNPs) were used to synthesize rice straw extract to mitigate heavy metal stress in rapeseed. This application led to enhanced antioxidant, peroxidase, catalase, ascorbate peroxidase activity and increased photosynthesis among other things[42].

[43]highlights the use of silver nanoparticles (AgNPs) in overcoming the drought stress by improving the water intake,

Vol. 19 (Supplementry Issue 3A), September 2025, ISSN 0973-8916 (Print)., 2230-7303 (Online)
10.5530/ctbp.2025.3s.3

shoot length, fresh and dry weight in lentils. AgNPs also improved germination percentage in lentils under drought conditions. Apart from this, AgNPs are used to mitigate salinity stress in plants by strengthening osmolality along with chloride, sodium and potassium concentration. AgNPs priming also stimulates germination in wheat grain [44].[45]tested Zinc oxide nanoparticles (ZnONPs) for salt stress tolerance in canola (*Brassica napus*) and observed upregulation of antioxidants, osmolyte biosynthesis and ionic regulation to overcome adverse effects of salinity. In another study, ZnONPs used on okra (*Abelmoschus esculentus* L.) elevated photosynthetic pigment production as well as improved catalase and antioxidant productivity [46].

A similar studyshows the benefits of green Copper nanoparticles (CuNPs) in minimizing the effect of salinity stress. Application of CuNPs improves Na^{+}/K^{+} ratio, promotes growth, elevates levels of glutathione, phenols and vitamin-C as compared to control samples. In tomato plants, CuNPs application boosts expression level of antioxidants and jasmonic acid genes alleviating salt stress. Parallelly, manganese nanoparticles (MnNPs) were used to mitigate salinity stress in pepper plants. MnNPs application showed improved root growth, reduced lignin production and decreased redistribution of Ca, Mn, Na, K contents between the root and the aerial parts as compared to untreated samples [47].

Green synthesized nanoparticles integrate within the plant system and strengthen plant growth and development (Figure 2). Their properties vary depending upon the plant source, physiological properties and application method [48]. Additionally, they do not deteriorate the environment as compared to synthetically synthesized nanoparticles. Overall, they provide a good alternative in resolving the impact of stress conditions in plants.

4. Nanoparticles in Agriculture: Nanofertilizers and Nanobiopesticides

One of the unavoidable components of Indian agriculture today is pesticides. There are numerous health and environmental risks that arise as a result of increased dosage of these pesticides. Nanotechnology has given rise to a new field of study and the creation of nanobiopesticides (Table 2). Nanotechnology research has produced a variety of nano-formulations, including nano-insecticides, nano-herbicides, nano-fungicides, and nano-nematicides, that can be used to protect crops

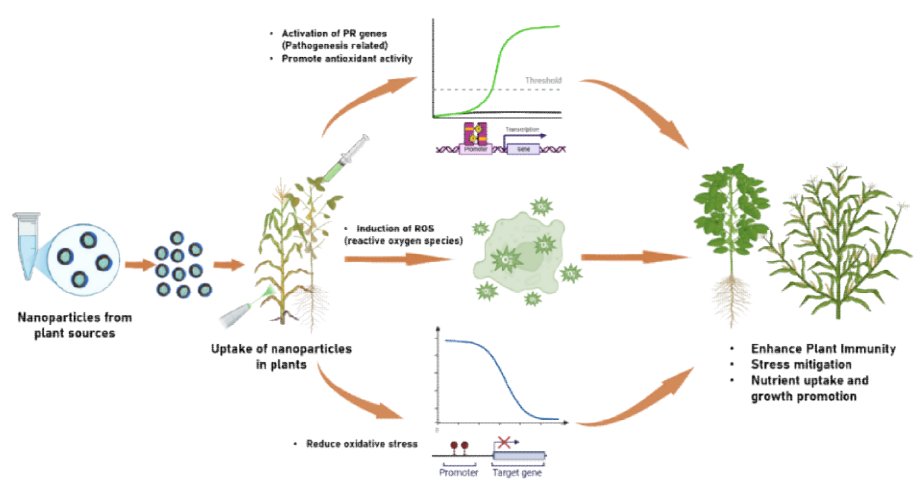

Fig. 2: Overview of Mechanism of Action of Green Synthesized nanoparticles within the plant system

Vol. 19 (Supplementry Issue 3A), September 2025, ISSN 0973-8916 (Print)., 2230-7303 (Online)
10.5530/ctbp.2025.3s.3

Table 2: The following table shows the key differences between nanobiopesticides and conventional pesticides

Feature	Nanobiopesticides	Conventional Pesticides	References
Definition	Pesticides formulated using nanotechnology, often incorporating biological components.	Chemical or biological substances used to control pests in agriculture.	[57]
Mode of Action	Controlled and targeted release, enhancing efficiency with minimal use.	Broad-spectrum activity, often requiring higher doses.	[58]
Composition	Engineered nanoparticles, bio-based materials, essential oils, or biopolymers.	Synthetic chemicals like organophosphates, carbamates, pyrethroids, or biological compounds.	[59,60]
Efficiency	Higher bioavailability and prolonged action due to nanoscale properties.	Rapid degradation and potential for resistance development.	[58]
Application Methods	Requires specialized techniques like nano-encapsulation, slow-release formulations.	Commonly sprayed or applied as dust, liquid, or granules.	[61,62]
Environmental Impact	Lower toxicity to non-target organisms and reduced residue buildup.	Can accumulate in soil and water, causing long-term environmental damage.	[59,63]
Regulatory Status	Emerging field with evolving regulations.	Well-established with clear regulations.	[64]
Toxicity	Typicallylower toxicity to humans and beneficial organisms.	Often toxic to humans, pollinators, and other non-target species.	[65]

[49]. The formulation of nanobiopesticides is based on their intended use, such as enhancing solubility, delaying the release of active components and preventing degradation. In order to accomplish these goals, changes in the chemical makeup of the carrier molecule have been made and categorized as clay-based nanomaterials, lipid-based formulations, organic polymer-based formulations, nanosized metals and metal oxides [50].

Since surfactant molecules are contained at the pesticide-water interface, an oil-in-water (O/W) emulsion is more frequently used as a nano-emulsion, in which the chemical's active ingredient is distributed as nanoscale droplets in water. Based on the amount and kind of surfactants, nano-emulsions are further divided into two categories: kinetically stable and thermodynamically stable. It is a thermodynamically stable nano-emulsion if the pesticide is partially soluble in the aqueous phase and a stable emulsion form spontaneously when the pesticide, surfactant, and water components are combined. The active ingredients insolubility causes the pesticide and surfactant to initially form a two-phase system. As a result, they mix together when sheared continuously, and the pesticide droplets in the nano-emulsion stay dispersed for a long time, making them kinetically stable [51].

Nano-suspension, also known as nano-dispersions, are made by spreading the insecticide in aqueous media as solid nanoparticles. The surfactant molecules in nano-dispersions are trapped at the particle surface, with the nonpolar parts attaching to the solid pesticide and the polar parts extending into the aqueous solution [52].

Vol. 19 (Supplementry Issue 3A), September 2025, ISSN 0973-8916 (Print)., 2230-7303 (Online)
10.5530/ctbp.2025.3s.3

The main application for these polymer-based pesticide nanocarriers is the gradual and regulated delivery of active chemicals to the intended location. Additionally, they can act as a protective reservoir and enhance dispersion in watery conditions. These include nano-encapsulation, nano-spheres, nano-gels, and nano-fibers. The term "nano-encapsulation" refers to a heterogeneous reservoir-type structure that is encased in a polymer coating or membrane and has an inner central chamber that restricts the hydrophobic or hydrophilic active ingredient. This formulation can protect the active component in the neem-azadiractin combination. The bioactive component is evenly distributed throughout the polymer matrix of these homogeneous vesicular structures, known as nanospheres. Hydrogel nanoparticles are another name for nanogels. They absorb more water because they are made by cross-linking polymeric particles with hydrophilic groups, an illustration of this is chitosan nanogel[53].

Solid nanoparticles can be employed as nanobiopesticides in addition to the formulations mentioned above. Through both sorption and abrasion, the inert dusts such as silica, alumina, and clay damage the wax layer on the insect cuticle causing the insect to become dehydrated and lose its bodily fluids. Given its added ability, plants become more resilient to biotic and abiotic challenges, nano-silica particles can be recommended as a viable option among solid nanoparticles [54].

The most favored metals for nanoparticles are copper, titanium oxide, and silver. Researchers study nanoparticles like AgNPs because of their virucidaland bactericidal properties. Its preference is increased by its higher surface area, crystalline structure, intrinsic charge, and low toxicity. TiO_2NP has demonstrated potent antibacterial and antifungal properties when applied to crops. At extremely low concentrations, copper formulations have been shown to be effective against pomegranate bacterial blight and to damage bacterial cell walls. Bacterial cells treated with CuNPs showed signs of cell wall damage [55].

Nonetheless, there are several benefits of using nanobiopesticides as opposed to traditional pesticides. Since most nanobiopesticide formulations are extremely target specific, nanotechnology provides a platform for creating innovative formulations of environmentally benign pesticides. In general, the effective use of pesticides can be increasedand residual and pollution can be decreased by targeted delivery and controlled release of nanobiopesticides. To administer pesticides, for instance, nano-microcapsule formulations use high polymer materials that are sensitive to light, temperature, humidity, enzymes, and soil pH, resulting in gradual release and protective performance making nanobiopesticides more advanced to future use [56].

5. Nanoparticles in Plant Immunity/ Plant Disease Management

Nanoparticles (NPs) have emerged as a promising tool in enhancing plant immunity and providing protection against phytopathogens. As the demand for increased crop production rises in the face of a rapidly changing environment, novel approaches to mitigate plant diseases and stressors are essential. NPs are being designed for plant disease management due to their unique physio-chemical properties and the ability to easily interact with plant cells. These engineered NPs have shown great potential in inhibiting pathogen infections while also promoting plant growth [66].

One prominent advantage is their ability to induce disease resistance. NPs such as silicon (SiNPs), silver (AgNPs), and magnesium oxide (MgONPs) have demonstrated the ability to trigger resistance in plants when used as pre-treatment against bacterial pathogens such as *Pseudomonas syringae*pv. This is attributed to their antiviral action and their ability to activate plant defense mechanisms [67].

Vol. 19 (Supplementry Issue 3A), September 2025, ISSN 0973-8916 (Print)., 2230-7303 (Online)
10.5530/ctbp.2025.3s.3

One such technique is nano-priming where seeds are treated with nanoparticles prior to sowing in order to improve germination, vigor, and growth. Specific nanoparticles induce the plant immune system promoting resistance to certain stresses [68,69]. A study done by [70] indicates that TiO_2 and Cerium oxide (CeO_2) nanoparticles can impact plant immunity by altering key signaling pathways, such as MAPK, and affecting the expression of immune-related genes. While these nanoparticles promote some aspects of early plant growth, the downregulation of critical immunity genes suggests that their effects may not be entirely beneficial. In particular, CeO_2 nanoparticles have ROS-scavenging properties that could lessen certain stress signals, yet both TiO_2 and CeO_2 nanoparticles may ultimately reduce overall immune responses in plants [71].

Various studies have hypothesized the potential of exogenous application of Fe_3O_4NPs to enhance crop growth, reduced heavy metal uptake and suppressed biofilm formation on food-associated bacteria. [72]investigated the physiological effects of Fe_3O_4NPs in plant defense against the TMV (Tobacco mosaic Virus) in *Nicotiana benthamiana* plant system and found that Fe_3O_4NPs are significantly more effective in preventing viral infection than bulk Fe_3O_4.Fe_3O_4NPs magnify antioxidant activity by increasing reactive oxygen species ROS production which subsequently upregulates salicylic acid (SA) production and the expression of pathogenesis-related (PR) genes, thereby promoting plant immunity and growth. Additionally, FeNPs have been shown to induce plant immunity against biotic stresses, as reported by [73].

[74]studied the positive impact of ZnONPs in increasing leaf dry weight, root yield, sugar content while declining disease severity. Similarly, [75,76]have demonstrated the ability of SiO_2NPs to enhance biomass and photosynthetic activity under certain conditions. Both ZnONPs and SiO_2NPs display high antiviral properties against TMV at low concentration (100ug mL^{-1}). When applied to the foliage, these NPs were absorbed and distributed throughout the plant system, leading to ROS accumulation and the activation of SA-induced PR gene upregulation boosting plant immunity. The antiviral mechanism of these nanoparticles is thought to involve the rapid deactivation of TMV through viral aggregation and fragmentation, providing a highly effective means of preventing infection [77].

These findings highlight the potential of NPs as a valuable tool in sustainable agriculture, offering a novel approach to enhancing plant immunity and disease resistance while also promoting growth and productivity.

Nanobioremediation

Over the years, there has been a steep increase in the degradation of the environment by various pollutants such as untreated waste from industries, chemical fertilizers and pesticides, oil spills and much more. Even though several methods are being researched to reduce the pollution, nanobioremediation is a new and coming technique. It allows bioremediation in a harmless and cost-effective manner. Unique properties of nanoparticles can be exploited for the advantage of bioremediation. Certain plant-derived nanoparticles have extraordinary absorbance and catalytic properties, diverse surface chemistry, customizable pore size and other options as compared to other methods [78].

Work done by [79] show the green synthesis of iron oxide nanoparticles from *Aerva lanata* flower extract and was used alongside a biosurfactant under optimal conditions to reduce the toxicity of soil contaminated with crude oil and heavy metals. Similarly, styrene contaminated soil environment was recovered using the nanobioremediation by *sunn hemp (C.juncea), zinnia (Z. violacea), marigolds (T. erecta*L.). Carbon-based nanoscale zero-valent iron from these plants was able to remove 100% styrene water and more than 60% styrene from soil [80].

A study utilizes SiO_2NPs in recovering pyrene from biodegradation of

Vol. 19 (Supplementry Issue 3A), September 2025, ISSN 0973-8916 (Print)., 2230-7303 (Online)
10.5530/ctbp.2025.3s.3

pyrene during algal growth of *Chlorella vulgaris.* SiO_2NPs can be utilized to improve microalgal growth while reducing pyrene biodegradation [81]. In[82,83],AgNPs synthesized from *Mimosa tenuiflora*and *Tricoderma*species have been used as photocatalysts to treat the effluent released in aquatic ecosystems and reduce the azo dye degradation respectively. Studies with *Delonix regia* leaves for AgNPs synthesis show similar catalytic properties in remedying the aquatic ecosystem [84,85].

These studies demonstrate the immense potential of nanobioremediation as a sustainable and efficient solution for mitigating environmental pollution across various ecosystems.

6. Challenges and Future Perspectives

The integration of agriculture and environmental remediation through the use of plant-derived nanoparticles presents significant opportunities to promote sustainable practices and tackle global food security challenges (Figure 3). Nevertheless, the road to mainstream adoption is riddled with obstacles that must be carefully negotiated. Although nanoparticles provide novel answers, their potential harm to human health and ecosystems remains a concern. Prolonged exposure to nanoparticles can disturb ecosystems, with some nanomaterials causing oxidative stress in plants, potentially impairing growth and development. Comprehensive assessments of long-term environmental consequences, toxicity, and bioaccumulation are required to ensure safety. Although there is potential for nanofertilizers, problems such as the leakage of nutrients while distribution and the overall efficiency of the nutrients once the fertilizer is delivered to the field still remain problematic. Compatibility with current agricultural infrastructure and high production costs must also be addressed.

Nanotechnology in agriculture has a complicated and underdeveloped regulatory environment. Uncertainty arises from the lack of precise regulations adapted to the special characteristics of nanomaterials. Establishing strict yet workable regulations requires cooperation between scientists, lawmakers, scientists and farmers. Another key success factor for nanoparticle-based technologies is its economic viability and societal acceptance. This might be hampered by high production costs, false information as well as lack of knowledge. Main challenge is to promote awareness and acceptance among the consumers and stakeholders by outreach and awareness initiatives.

In the future, plant-derived nanoparticles may improve soil fertility and crop production, thereby supporting sustainable practices. Metal oxide nanoparticles, for example, have shown

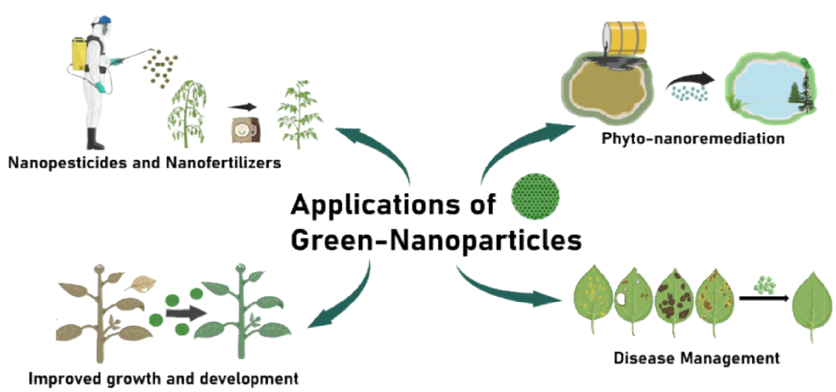

Fig.3: Illustration depicting major applications of Green synthesized nanoparticles in Agriculture and Environmental Remediation.

Vol. 19 (Supplementry Issue 3A), September 2025, ISSN 0973-8916 (Print)., 2230-7303 (Online)
10.5530/ctbp.2025.3s.3

promise in boosting plant growth and pest management while also providing environmentally acceptable alternatives to traditional agrochemicals. They also enable the precise delivery of nutrients and agrochemicals, lowering environmental impact and increasing application efficiency. These systems have the potential to revolutionize pest control and nutrition management while reducing waste. The growing global interest, particularly in developing nations, emphasizes nanotechnology's potential to alleviate food security issues. Continued research efforts will stimulate innovation and implementation in the most underserved areas.

Future study should focus on assessing the long-term effects of nanoparticles on soil health, crop productivity, and biodiversity. Nanotechnology can be integrated into traditional farming practices through collaboration between academics and farmers, ensuring that it complements and improves existing approaches. Agriculture can address these difficulties and leverage the revolutionary potential of plant-derived nanoparticles to implement creative and sustainable solutions that balance productivity and environmental protection. The collaboration of scientists, politicians, and industry participants will be critical to attaining this ambition.

Conclusion

The use of plant-derived nanoparticles in nanotechnology has huge opportunities for sustainable agriculture and environmental rehabilitation. This review covers the synthesis of the nanoparticles, their distinguishing properties, and numerous uses of green nanomaterials, focusing on their significance in tackling critical global concerns such as food security, environmental degradation, and agricultural productivity. In contrast to chemically created nanoparticles, plant-derived nanomaterials offer an environmentally friendly and economically acceptable alternative, promoting sustainable development objectives by minimizing chemical consumption and mitigating ecological damage.

In agriculture, plant-derived nanoparticles have shown usefulness in boosting crop resistance, easing abiotic stresses, and promoting nutrient efficiency. Applications such as nanofertilizers and nanobiopesticides allow precision-based delivery, decreasing chemical waste and residues while enhancing crop production and soil health. Nanofertilizers improve nutrient accessibility and absorption, hence promoting plant growth and mitigating environmental discharge. Likewise, nanobiopesticides offer controlled release and focused efficacy, markedly reducing the ecological impact relative to traditional chemical pesticides. These advances foster an environmentally sustainable agriculture paradigm, harmonizing productivity with conservation.

Environmental remediation represents a field in which plant-derived nanoparticles have a huge potential. Their potential to absorb heavy metals and breakdown organic toxins offers an acceptable treatment for repairing damaged ecosystems. Nanoparticles made from sources including neem, aloe vera, and citrus peels have proven success in removing harmful substances from water and soil, underscoring their value in sustainable pollution management. Furthermore, improvements in nanoremediation techniques using green nanomaterials solve major environmental challenges, such as oil spills and industrial waste, with greater efficiency and less secondary pollution.

It is yet unclear how dangerous nanoparticles, sometimes known as nanobiopesticides, could be to the environment and human health. Because nanobiopesticides are reportedly more toxic and persistent than their conventional equivalents, they may also cause new types of contamination of soils and streams through their use. Thus, a deeper comprehension of the fate and impact of nanobiopesticides following their application is necessary. Additionally, high production costs and little public awareness pose impediments to the

Vol. 19 (Supplementry Issue 3A), September 2025, ISSN 0973-8916 (Print)., 2230-7303 (Online)
10.5530/ctbp.2025.3s.3

broader application of these technologies. Collaborative efforts among researchers, politicians, and industry stakeholders are vital to develop solid regulatory standards, maintain safe practices, and encourage societal acceptance through education and outreach.

Looking ahead, future research should prioritize the scalability of green nanoparticle production, cost reduction measures, and the development of multifunctional nanomaterials customized to specific agricultural and environmental demands. Exploring the synergistic benefits of combining different types of nanoparticles and incorporating them into existing agricultural frameworks will further boost their efficacy. Additionally, multidisciplinary collaboration across molecular biology, material science, and agricultural technology will encourage innovation and optimize the usage of plant-derived nanomaterials.

In conclusion, plant-derived nanotechnology represents a big step toward sustainable and resilient agricultural systems. By utilizing the unique features of green nanoparticles, we can achieve precision agriculture, improved environmental management, and less dependence on dangerous pesticides. While problems exist, the continuing search and suitable application of this technology will create the way for a greener, more sustainable future in agricultural and environmental sectors. The combined efforts of scientific communities, regulatory authorities, and global stakeholders will be vital in unlocking the full potential of plant-derived nanomaterials, producing meaningful and lasting solutions to some of the world's most pressing challenges.

Conflicts of interest

The authors declare that they have no competing interests.

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