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REVIEW ON : SUSTAINABLE INNOVATIONS WITH GREEN-SYNTHESIZED NANOPARTICLES – ADVANCING ECO-FRIENDLY SOLUTIONS

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ABSTRACT:
New technologies are being explored at a rapid pace to improve crop yield and productivity with minimum detrimental effects on the environment. Nanoparticles (NPs) of unique physicochemical properties synthesized through green processes can play an attractive role in sustainable agriculture. This review provides a comprehensive overview of their uses in enhancing crop's growth, managing nutrients, eliminating pests and diseases, and improving soil quality. In addition to their major benefits, nanoparticles for agricultural use also pose several risks and challenges. Further, this review, compares how green synthesis differs from conventional synthesis methods and emphasizes the potential for sustainable agriculture through the application of Green-synthesized Nanoparticles (GNPs).

KEYWORDS: Nanoparticles (NPs), Green-synthesized Nanoparticles (GNPs), Physicochemical properties, Sustainable agriculture, Conventional synthesis methods
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1. INTRODUCTION:

Agricultural sustainability, especially as it relates to agroecology or regenerative farming, is the practice of producing food, fiber, and other agricultural products sustainably, by preserving the environment and without exhausting natural resources [i]. This helps to improve biodiversity, soil health, water conservation with fewer artificial inputs and greenhouse gases. Sustainable agriculture helps in food security, improves rural livelihoods, and counters environment issues such as reducing the pollutant and environmental degradation [ii].
Farming will need to increase food production by 70% to meet this growing demand, which is roughly equal to the size of the world's population by 2050. Still, there are a few challenges to achieving agricultural sustainability in a farming context. This rising need for agricultural

expansion often leads to adverse environmental impacts, including excessive use of chemical fertilizers, pesticides, and herbicides-resulting in soil degradation, water contamination, biodiversity loss, and negative effects on human health. Furthermore, climate change-induced extreme weather events and unpredictable precipitation patterns further complicate agricultural sustainability [iii].

Nanotechnology has recently become an ingenious resolution for tackling these challenges. Nanotechnology deals with the manipulation of materials at the nanoscale (which is usually defined as having less than 100 nanometers) where Nanoparticles (NPs) demonstrate unique physicochemical properties compared with their macroscopic bulk counterpart [iv]. Due to these properties, nanoparticles are being recognized as potential agents in diverse agriculture applications including crop production, soil good management practices, and sustainable agriculture [v].

Green-synthesized Nanoparticles (GNPs) have attracted considerable interest among the nanotechnology-based approaches as healthy counterparts to traditionally made nanoparticles. Such NPs are synthesized using ecological-friendly methods, like plant-mediated, microbial-assisted, and bio-waste-derived synthesis, less toxic chemicals are needed for their preparation [vi].

This review article seeks to investigate the significance of GNPs in promoting sustainable agricultural practices. It will analyze different methods of green synthesis, their distinctive physicochemical characteristics, and their prospective applications in enhancing crop growth, managing nutrients, controlling pesticides and diseases, and remediating soil [vii]. Furthermore, the paper will address the advantages, potential risks, and challenges linked to the application of these NPs in agriculture. An examination of regulatory frameworks for the safe and responsible use of NPs in farming will also be included [viii]. Ultimately, the article will offer insights into future developments regarding the application of GNPs, emphasizing their capacity to transform sustainable agricultural methodologies [ix].

2. GREEN SYNTHESIS OF NANOPARTICLES (GNPS):

Essentially, green synthesis is a type of synthesized process that does not require harsh chemicals to form NPs. This method relies on natural sources, such as plants, bacteria, fungi, and even agricultural waste, rather than toxic substances. The workup scheme is also not just more affordable but also more straightforward and ultimately greener [vi]. One of the biggest reasons green syntheses are gaining attention in nanotechnology is because traditional methods-both chemical and physical come with a lot of drawbacks. They generate waste that can be harmful to both the environment and human health [x].

It uses plant extracts, microbial cultures, and agricultural waste as biological precursors, decreasing dependence on synthetic chemicals [iv]. Flavonoids, terpenoids, proteins, polysaccharides, etc. are natural biomolecules that serve as bio-reductants and capping agents, thus, replacing the use of toxic chemicals, [xi]. In contrast to conventional synthesis, which leaves behind solvents, toxic byproducts, and heavy metal contaminants, green synthesis yields biodegradable and environmentally begin byproducts [ix]. Due to their ability to produce NPs at room temperature and ambient pressure, most of the green synthesis methods save energy and carbon footprint [x]. The reactions are carried out in an aqueous solution or biocompatible solvents eliminating organic solvents (such as chloroform, methanol, and acetone) which are hazardous to the environment and health [viii]. NPs biosynthesized employing green approaches are more biocompatible and less toxic to soil microorganisms, plant organisms, and aquatic organisms as compared to their chemically synthesized counterparts [xii]. The agriculturally undeniable application of green synthesis is also based on the utilization of inexpensive plant materials, microbes, and waste products [xiii].

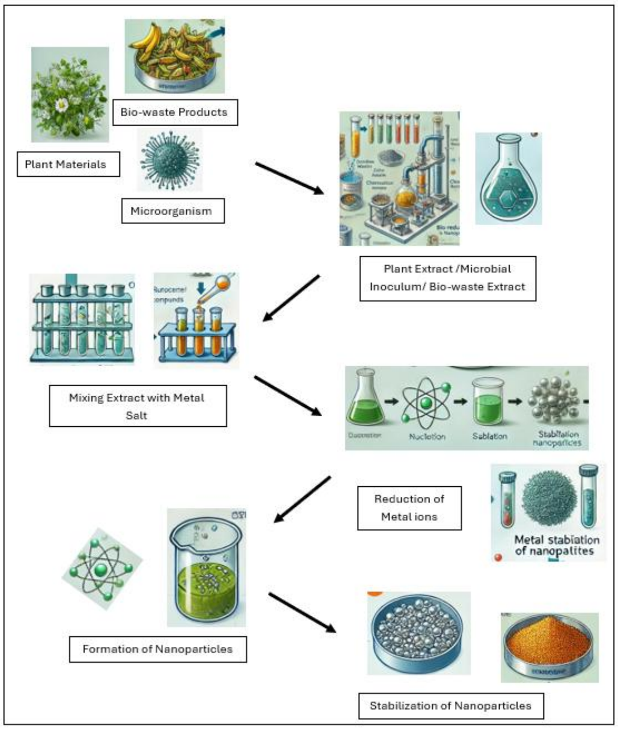

Fig. 1: Green-Synthesis of Nanoparticles (GNPs)

Table 1: COMPARISON BETWEEN GREEN-SYNTHESIS AND CONVENTIONAL SYNTHESIS OF NANOPARTICLES

Criteria	Green Synthesis	Conventional Synthesis	Citations
Process	Biocompatible, eco-friendly, uses natural reducing and stabilizing agents.	Requires toxic chemicals, generates hazardous byproducts.	[xv]
Reducing Agent	Phytochemical, microbial enzymes, bio-waste extracts.	Chemical reductants like sodium borohydride, hydrazine.	[xvi]
Stabilizing Agents	Proteins, polysaccharides, flavonoids act as natural capping agents.	Synthesis surfactants like CTAB, PVP, and PEG.	[xiv]
Toxicity	Low (biodegradable, non-harmful to soil and water).	High (toxic residues can accumulate in ecosystems).	[xiii]
Energy Consumption	Low (room temperature, aqueous-based reactions).	High (often requires heat, UV, microwave, or chemical activation).	[xvi]
Reaction time	Moderate (may take hours to days for complete synthesis).	Rapid (minutes to hours due to strong chemical catalysts).	[xiv]

Scalability	High (cost-effective, feasible for large-scale production).	Expensive, requiring controlled environments and hazardous waste management.	[xii]
Particle Size Control	Less Precise but tunable by modifying extract concentration and pH.	Highly controlled with specific chemical reagents and templates.	[xi]
Environmental Impact	Minimal (uses renewable resources, reduces chemical waste).	High (generates hazardous waste, pollution risks).	[xv]
Applications	Ideal for agriculture, medicine, food safety, and environmental remediation.	Used in electronics, industrial coatings, and pharmaceuticals but raises safety concerns.	[xvi]

2.1 PLANT-MEDIATED SYNTHESIS OF NANOPARTICLES:

The Nanoparticle (NP) synthesis mediated by plants is one of the most eco-friendly, cost-effective, and scalable methods for producing nanomaterials. Instead of using toxic chemical agents, this approach relies on the natural phytochemicals present in plant extracts to act as reducing, stabilizing, and capping agents [xv]. These phytochemicals include flavonoids, alkaloids, tannins, terpenoids, polyphenols, and proteins, which help convert metal ions into NPs while ensuring stability and preventing aggregation [xiv]

One of the biggest advantages of this method is its simplicity and sustainability. Unlike conventional chemical synthesis, which often requires high temperatures, hazardous solvents, and complex processing steps, and complex processing steps, plant-mediated synthesis is a one-step, energy-efficient, and biocompatible process [xiii].

The basic concept of plant-mediated synthesis is that there is a bioreduction process wherein metal ions are transformed into nanoparticles (NPs) through the action of phytochemicals obtained from plants. He phytochemicals in the plant extract provide electrons to the metal ions (Mn+), thereby reducing them to their elemental state (MO). For instance, the conversion of silver ions (Ag+) into silver nanoparticles (AgNPs) occurs due to the antioxidants present in plant extractives. It is observed that once precipitated, metal atoms begin to agglomerate, forming nuclei which further develop into NPs. The NPs formed are not allowed to aggregate due to their stabilization by biomolecules from the plants. The diversity in these reducing and stabilizing agents leads variabilities in size, shape as well as properties of NPs synthesized [xiv].

Table 2: PLANT-MEDIATED SYNTHESIS OF NPS AND THEIR ADVANTAGES

Plant Source	Major Bioactive Compounds	Nanoparticles Synthesized	Advantages	Citations
***Azadirachta indica* (Neem)**	Flavonoids, Terpenoids, Polyphenols	AgNPs, AuNPs, ZnONPs	Strong antimicrobial & antifungal activity, eco-friendly alternative to synthetic pesticides	[xv]
Aloe vera	Polysaccharides, Proteins, Phenolics	AgNPs, AuNPs, CuONPs	High nanoparticle yield, biocompatibility, wound healing applications	[xvii]

***Ocimum sanctum* (Tulsi)**	Eugenol, Flavonoids, Alkaloids	AgNPs, ZnONPs	Antioxidant-rich, eco-friendly, used in plant disease management	[xviii]
Moringa oleifera	Phenolics, Saponins, Tannins	AgNPs, FeONPs	Strong reducing ability, biodegradable, soil-friendly applications	[xix]
***]Cymbopogon citratus* (Lemongrass)**	Citral, Flavonoids, Phenolics	AgNPs, AuNPs	Rapid synthesis, Potent antimicrobial properties	[xx]
***Curcuma longa* (Turmeric)**	Curcumin, Phenolics, Tannins	AgNPs, CuONPs, Fe_3O4NPs	Anti-inflammatory properties, stable nanoparticle synthesis	[xxi]
***Zingiber officinale* (Ginger)**	Gingerol, Shogaol, Flavonoids	AgNPs, ZnONPs	Effective against plant pathogens, biofilm disruption	[xxii]
***Camellia sinensis* (Green Tea)**	Catechins, Theaflavins, Polyphenols	AgNPs, AuNPs	Antioxidant-rich, high stability & dispersion in solutions	[xxiii]
Eucalyptus globulus	Tannins, Terpenoids, Phenolics	AgNPs, TiO_2NPs	Strong antifungal properties, fast reductio process	[xxiv]
***Allium sativum* (Garlic)**	Allicin, Sulfur compounds, Flavonoids	AgNPs, CuONPs	Potent antimicrobial & antiviral properties, natural pesticide potential	[xxv]

*AgNPs – Silver Nanoparticles, AuNPs – Gold Nanoparticles, ZnONPs – Zinc Oxide Nanoparticles, CuONPs – Copper Oxide Nanoparticles, FeONPs – Iron Oxide Nanoparticles, Fe_3O4NPs – Magnetite Nanoparticles, TiO_2NPs – Titanium dioxide Nanoparticles

Some plant-mediated NPs, particularly those derived from medicinal plants like *Azadirachta indica* (Neem) and *Crcuma longa* (Turmeric), resemble quantum dots in their remarkable properties of fluorescence and light absorption shifts. Therefore, their application is not limited to agriculture but can also be extended to bio-imaging, sensor development, and smart coatings for crops. A novel approach within the synthesis of plant-mediated NPs is termed "hybrid green synthesis", involving the use of extracts from different plants. Combining extracts of Neem, Tulsi, and *Aloe vera* results in NPs with enhanced antifungal and antioxidant properties compared to those obtained from a single plant extract. This approach will enhance the bioactivity and might lead to tailored NPs for particular crops and soil conditions [xvii].

Different plant species contain different unique bioactive compounds, which in turn influence the yield, shape, and stability of the NPs produced. Below is a comparison of some commonly used plant extracts and their applications [xviii]. Despite its potential, plant-mediated synthesis faces several challenges includes compositional variability of the plant extracts such as the climate, age of the plant, and method of extraction influence of the percentage composition of phytochemicals. The Stability and shelf life of many green NPs show tendency to aggregate over time, hence their effectiveness is reduced.

Table 3: PHYTOCHEMICAL INFLUENCE ON NANOPARTICLE SHAPE AND STABILITY

Phytochemical Group	Common Plant Sources	Effect on Nanoparticles	Nanoparticle Shape	Citations
Tannins & Polyphenols	Tea (*Camellia sinensis*), Pomegranate (*Punica granatum*), Oak Bark (*Quercus sp.*)	Act as strong reducing and capping agents; promote oxidation-resistant nanoparticles	Spherical	[xv]
Flavonoids & Alkaloids	Neem (*Azadirachta indica*), Citrus Fruits (*Citrus sp.*), Turmeric (*Curcuma longa*)	Facilitate anisotropic growth; influence crystallization patterns	Triangular, Hexagonal	[xvi]
Proteins & Sugars	Aloe Vera (*Aloe barbadensis*), Moringa (*Moringa oleifera*), Banana Peel (*Musa sp.*)	Enhance stabilization; prevent aggregation; promote long-term colloidal stability	Rod-shaped	[xix]
Terpenoids & Saponins	Tulsi (*Ocimum sanctum*), Ginseng (*Panax ginseng*), Fenugreek (*Trigonella foenum-graecum*)	Help in nucleation; modulate surface energy and zeta potential	Irregular, Branched	[xxi]
Phenolic Acids	Clove (*Syzygium aromaticum*), Cinnamon (*Cinnamomum verum*), Grapes (*Vitis vinifera*)	Induce controlled nanoparticle growth; provide antioxidant coating	Nano-clusters	[xxx]
Steroids & Lignins	Garlic (*Allium sativum*), Pine (*pinus sp.*), Wheat Bran (*Triticum aestivum*)	Enhance thermal and chemical stability of nanoparticles	Prismatic, Cubic	[xxxi]

2.2 MICROBIAL-ASSISTED SYNTHESIS OF NANOPARTICLES:

One new approach of green nanotechnology is the microbial-assisted synthesis of nanoparticles which utilizes the native biochemical activities of microorganisms such as bacteria, fungi, and algae to biosynthesize and stabilize the NPs. These microorganisms excrete a host of different enzymes, proteins, and metabolites which not only aid in the bioreduction of metal ions to stable NPs, but also serve as protective agents to control their size and morphology [xxvii].

Microbial systems have some singular benefits when compared to other methods of green synthesis. Microbes are able to control the size of the NPs through intracellular and extracellular mechanisms which result in size uniformity. Microbes are more efficient than plants when it comes to the conversion of metal ions, which make microbes more useful for industrial applications. The cultivation of microbes is easily scaled in bioreactors, which makes these methods feasible for the bulk production of NPs. In contrast to chemical synthesis, microbial-assisted synthesis does not employ toxic reducing agents and stabilizers [xviii-xxx]. Microbial metabolism and biomolecules determine the rate at which different microbes synthesize NPs. The microbes possess some primary secreted enzymatic extracellular NADH-peroxidases that catalyze the reduction of metal ions into their corresponding nanoparticles. For example, the *Pseudomonas aeuroginosa* reduces silver ions to silver NPs using secreted silver ion reductase enzymes. Simple form of extracting NPs and it is amenable to programmatic scaling. Microbial metal ions diffuse into cells, where they are entrapped and reduced by some intracellular biomolecules like proteins, glutathione, and some metal binding peptides. For example, *Fusarium oxysporum* assimilates gold ions and reduces them within the cytoplasm to form gold NPs. Enhanced control level over upper limits of size and stability but entails cell lysis for NP harvest [xxv-xxx].

Microbial nanoparticle synthesis is an evolving field, and researchers are now going so far as using synthetic biology and genetic engineering to persistently customize NP synthesis. Exopolysaccharide (EP)-Mediated Microbial-Synthesis of NPs involving less unpredictability and More Homogeneity Traditional microbial-assisted synthesis normally exhibits less predictability concerning variation of size, shape and stability of the NPs. Nonetheless, genetically modified microbes can be engineered to address these inconsistencies, leading to a more consistent and scalable process [xxxvii]. Furthermore, with the recent innovation of genome engineering methods including CRISPR-Cas9 as well as recombineering, scientists are now capable of altering bacteria and fungi in predictable and controllable ways to maximize their NP biosynthesis. Some bacteria and fungi produce such enzymes (e.g., nitrate reductases, hydrogenases and oxidoreductases) to reduce metal ions into NPs. The efficiency of NP synthesis can be greatly increased by overexpressing the genes encoding these enzymes [xxxviii]. Genetically modified *E. coli* that produces increased amounts of NADH-dependent reductases has shown better yields and enhanced stability for gold and silver NPs (AuNPs, AgNPs) when compared to their natural counterparts [xxxix].

Table 4: MICROBIAL-ASSISTED SYNTHESIS OF NPS AND THEIR APPLICATIONS

Microorganisms	Type	Nanoparticles Synthesized	Key Mechanism	Applications	Citations
Pseudomonas aeruginosa	Bacteria	AgNPs, ZnONPs	Extracellular enzyme-mediated reduction	Antibacterial coatings, pest control	[xxv]
Bacillus subtilis	Bacteria	AuNPs, TiO_2NPs	Peptide and enzyme secretion	Biosensors, nanofertilizers	[xxvi]
Aspergillus flavus	Fungi	AgNPs, FeONPs	Fungal Metabolite reduction	Antifungal treatments	[xxvii]
Fusarium oxysporum	Fungi	AuNPs, ZnONPs	Intracellular bioreduction	Soil remediation	[xxviii]
Spirulina platensis	Algae	AgNPs, CuNPs	Biomass-mediated synthesis	Slow-release fertilizers	[xxix]

Escherichia coli	Bacteria	AgNPs, PdNps	Electron transfer-driven bioreduction	Heavy metal detoxification, catalysis	[xxx]
Lactobacillus spp.	Bacteria	AuNPs, MgONPs	Metabolite-assisted reduction	Wound healing, antimicrobial agents	[xxxi]
Streptomyces sp.	Actinobacter	Fe_2O_3NPs, ZnONPs	Secondary Metabolite reduction	Bioremediation, plant growth enhancers	[xxxii]
Trichoderma harzianum	Fungi	AgNPs, SeNPs	Enzyme-mediated biosynthesis	Plant disease control	[xxxiii]
Penicillium chrysogenum	Fungi	AuNPs, CuONPs	Protein and polysaccharide-mediated reduction	Bio-imaging, drug delivery	[xxxiv]
Chlorella vulgaris	Algae	AgNPs, ZnONPs	Algal metabolite-driven reduction	Soil remediation, nutrient delivery	[xxxv]
Saccharomyces cerevisiae	Yeast	SeNPs, AuNPs	Biogenic synthesis via intracellular accumulation	Antioxidant supplements, biosensors	[xxxvi]

*AgNPs – Silver Nanoparticles, AuNPs – Gold Nanoparticles, ZnONPs – Zinc Oxide Nanoparticles, CuONPs – Copper Oxide Nanoparticles, FeONPs – Iron Oxide Nanoparticles, Fe_3O4NPs – Magnetite Nanoparticles, TiO_2NPs – Titanium dioxide Nanoparticles, PdNps – Palladium Nanoparticles, SeNPs – Selenium Nanoparticles, MgONPs – Magnesium oxide Nanoparticles, Fe_2O_3NPs – Ferric oxide Nanoparticles

Adjusting microbial genetics can change both the shape and size of nanoparticles by modifying how biomolecules interact during their synthesis. For instance, when certain capping protein genes were deleted in *Pseudomonas fluorescens*, the result was rod-shaped NPs. In contrast, overexpressing those genes produced spherical NPs [xl]. By altering their metabolic processes, microbes can be engineered to use cheaper resources, such as agricultural waste, while still creating high-quality NPs. For example, a modified version of *Bacillus subtilis* was able to generate iron oxide nanoparticles (FeONPs) from organic waste, making the whole process cost-effective and eco-friendly [xxxviii]. Furthermore, these customized microbes can coat the NPs with biodegradable materials like polysaccharides, proteins, or lipids, which promote safe breakdown in the environment [xxxvii]. Moreover, these specially engineered microbes can wrap nanoparticles in biodegradable materials such as polysaccharides, proteins, or lipids, facilitating their safe breakdown in the environment [xxxvi].

Rather than depending on just one type of microbe, researchers are now trying out combinations of different microbes—like bacteria, fungi, and algae—to improve the production of NPs. For instance, when they co-cultured *Bacillus subtilis* with *Aspergillus niger*, they saw a 30% boost in the yield of zinc oxide nanoparticles (ZnONPs) compared to using just a single strain [xlii]. This approach is especially beneficial for creating high-quality nanofertilizers that release nutrients more efficiently. Additionally, nanomaterials made from chitosan, cellulose, and alginate break down naturally while promoting plant growth [xliii]. Chitosan-coated nanoparticles serve as biodegradable slow-release fertilizers, allowing plants to absorb nutrients gradually [xliv]. Soy protein and whey protein nanoparticles are becoming increasingly popular for their ability to deliver pesticides steadily while naturally breaking down in the soil. Research by Sharma et al. (2021) demonstrated that whey protein-stabilized silver nanoparticles (AgNPs) exhibited significant antifungal properties against plant pathogens and safely decomposed within 30 days. Additionally, lipid nanoparticles can encapsulate pesticides, fertilizers, or growth regulators, which helps ensure a controlled release and prevents environmental build-up. According to Verma et al. (2021), lipid-coated zinc oxide nanoparticles (ZnONPs) also improved soil nutrient retention and are completely biodegradable [xli, xlii].

2.3 BIO-WASTE-DERIVED SYNTHESIS OF NANOPARTICLES:

Utilizing agricultural waste, fruit peels, and leftovers from the food industry to create nanoparticles is a promising move towards a circular bioeconomy. Rather than throwing away organic waste, we can transfer it into useful nanomaterials, which helps to reduce costs and reduce environmental impact [xxxi]. Researchers have already looked into a variety of waste materials, including banana peels, orange peels, sugarcane bagasse, and used tea leaves, for their potential to produce NPs.

With the increasing demand for eco-friendly nanotechnology, researchers are turning to bio-waste-derived synthesis as a promising method for producing NPs. Items like agricultural leftovers, fruit peels, and food industry byproducts—previously considered waste—are now being transformed into valuable materials for the green synthesis of NPs [xxxviii]. This technique aligns with the principles of a circular bioeconomy and waste valorization, offering a cost-effective and sustainable solution. By utilizing agro-waste, we can lower production costs while also helping to reduce pollution [xxxv]. A variety of bio-wastes are rich in compounds such as polyphenols, flavonoids, tannins, and alkaloids, which act as natural reducing and stabilizing agents during the NP formation process [xlv]. Unlike traditional chemical synthesis, this approach generates minimal toxic byproducts, leading to safer uses in agriculture, healthcare, and environmental remediation [xlvi].

NPs derived from bio-waste are usually created using a variety of plant-based or microbial reducing agents that can convert metal ions into NPs under mild conditions. The bioactive compounds present in these bio-waste materials—such as polyphenols, flavonoids, and sugars—play a dual role as reducing and stabilizing agents in this process [xlvii]. They assist in the eco-friendly creation of nanoparticles by stopping them from sticking together and helping them stay stable while they're suspended. For instance, agricultural waste such as rice husks, fruit peels, and used coffee grounds has been utilized to make metal oxide nanoparticles (MNPs), gold nanoparticles (AuNPs), and silver nanoparticles (AgNPs) [xlviii]. This process involves extracting organic compounds from these bio-wastes, which serve as capping agents to keep the particles at a uniform and controlled size.

Among the metal NPs commonly produced from biological waste, silver, gold, and copper stand out. Silver nanoparticles have gained significant interest for their antimicrobial properties, positioning them as excellent options for use in medicine, water purification, and food packaging [xlix]. Research shows that synthesizing silver NPs from agricultural waste leads to the production of smaller and more uniform particles, which exhibit enhanced biological activity [xliii].

Table 5: BIO-WASTE-DERIVED NANOPARTICLES AND THEIR APPLICATIONS

Bio-waste Source	Nanoparticles Synthesized	Mechanism of Synthesis	Applications	Citations
Banana Leaf	AgNPs, ZnONPs	Rich in antioxidants & polyphenols	Antibacterial coatings, plant growth enhancers	[xxxviii]

		aiding reduction & stabilization		
Orange Peels	AgNPs, CuNPs	Citric acid and flavonoids act as reducing agents	Antifungal agent, water purification	[xlix]
Sugarcane Bagasse	AuNPs, TiO_2NPs	Contains lignin and cellulose aiding nanoparticle stabilization	Soil remediation, biosensors	[xliv]
Tea Waste	FeONPs, AgNPs	Rich in Catechins and polyphenols, excellent for bio-reduction	Antioxidants, pest control, antimicrobial coatings	[xxxix]
Coffee Grounds	AgNPs, CuNPs	Caffeine and phenolic compounds facilitate nanoparticle formation.	Sustainable Pesticides, wastewater treatment	[xl]
Coconut Husk	AgNPs, ZnONPs	High starch and polyphenol content aid reduction	Seed coatings, antifungal treatments	[l]
Pineapple Peels	AuNPs, FeONPs	Presence of bromelain and organic acids accelerates NP synthesis	Drug delivery, biomedical applications	[xlvi]
Grape Pomace	AgNPs, TiO_2NPs	Polyphenols and tannins act as natural reducing agents	Food preservation, antimicrobial films	[xlv]
Tomato waste	AgNPs, CuONPs	Lycopene and Flavonoids promote metal ion reduction	Antibacterial coatings, water filtration	[xliii]
Garlic Peel	AgNPs, ZnONPs	High sulfur content supports effective nanoparticle synthesis	Antifungal applications, biomedical use	[li]
Papaya Leaves	AgNPs, CuONPs	Enzymes and alkaloids assist in metal ion bioreduction	Wound healing, antioxidant agents	[lii]

*AgNPs – Silver Nanoparticles, AuNPs – Gold Nanoparticles, ZnONPs – Zinc Oxide Nanoparticles, CuONPs – Copper Oxide Nanoparticles, FeONPs – Iron Oxide Nanoparticles, Fe_3O4NPs – Magnetite Nanoparticles, TiO_2NPs – Titanium dioxide Nanoparticles

Additionally, metal oxide nanoparticles like zinc oxide (ZnO) and titanium dioxide (TiO_2) are widely employed for purposes such as photocatalysis, environmental cleanup, and sensor technology. Utilizing bio-waste for the environmentally friendly synthesis of these NPs decreases reliance on hazardous chemicals that are typically involved in traditional methods

[liii]. Besides inorganic nanoparticles, bio-waste-derived polymers such as chitosan and cellulose are also being utilized to create biodegradable polymeric nanoparticles, which have valuable applications in drug delivery, wound healing, and biosensors [liv]. Creating nanoparticles from bio-waste is also beneficial for the environment. By making use of organic waste that would otherwise be sent to landfills, this approach helps reduce waste buildup, thus decreasing soil and water pollution. Moreover, the bio-synthesis process avoids harmful solvents and chemicals that are typically found in traditional methods, leading to a smaller environmental impact [lv]. Economically, utilizing inexpensive and readily available bio-waste materials provides a significant financial edge over conventional chemical techniques, making this process scalable and viable for industrial applications [lvi].

3. PHYSICOCHEMICAL PROPERTIES OF GREEN-SYNTHESIZED NANOPARTICLES:

Green-synthesized nanoparticles (GNPs) are becoming an exciting alternative to traditionally created NPs. They are eco-friendly, cost-effective, and can be used in a wide range of applications, including agriculture, medicine, and environmental cleanup. The key characteristics of these nanoparticles—like their size, shape, surface charge, stability, and biodegradability—significantly influence how well they perform their intended functions [lvii]. Unlike chemically synthesized nanoparticles that typically rely on harmful reducing agents, gold nanoparticles (AuNPs) are produced using natural resources like plant extracts, microorganisms, and organic waste. These biological elements not only act as reducing agents but also improve the stability of the nanoparticles and their compatibility with living organisms [lviii].

In the realm of agriculture, one of the most significant aspects of GNPs is their size and shape, which influence how they interact with plant surfaces, soil, and microbial life. Smaller nanoparticles, which have a greater surface-area-to-volume ratio, tend to be more reactive and are easily absorbed by plant roots and leaves, thereby improving nutrient uptake and pest management [lix]. Moreover, the inclusion of biomolecules such as flavonoids, polyphenols, and proteins during the green synthesis process affects the structural integrity of the NPs, enhancing their stability and decreasing the likelihood of clumping together [lx].

Another significant advantage of green-synthesized nanoparticles (GNPs) is their ability to break down naturally and their compatibility with biological systems, which helps to mitigate long-term environmental risks [lxi]. In contrast to synthetic nanoparticles, which can build up and harm ecosystems, GNPs decompose over time due to the organic stabilizers used during their creation [lxii]. This property makes them especially useful in precision agriculture, where the controlled release of nutrients or pesticides can improve crop yields while reducing reliance on excessive chemicals [lxiii].

Moreover, the stability and controlled release mechanisms of green nano fertilizers are crucial properties that influence their long-term effectiveness in agriculture [lxiv]. The biological capping agents in GNPs not only help to keep their structure stable but also enable a gradual and sustained release of active compounds, which improves absorption by plants [lxv]. For example, zinc oxide (ZnO) and silica-based GNPs have demonstrated the ability to enhance plant growth and disease resistance by ensuring a lasting supply of vital nutrients [lxvi].

By fully understanding and refining these physicochemical properties, researchers can boost the effectiveness of GNPs in sustainable farming. This approach not only lessens the reliance on synthetic fertilizers and pesticides but also encourages more environmentally friendly agricultural practices [lxvii].

3.1 SIZE, SHAPE, AND SURFACE AREA:

The dimensions, shape, and surface area of nanoparticles are essential factors that influence their interactions in biological systems and their effectiveness in agriculture. NPs made using plant extracts or microbes generally measure between 1 and 100 nm [lxviii]. This small size helps them penetrate plant cells more easily, which in turn promotes better absorption of nutrients and active substances [lxix]. For example, silver nanoparticles (AgNPs) measuring between 10 and 20 nm have shown enhanced antibacterial properties against plant pathogens, thanks to their greater surface interactions [lxx]. Gold nanoparticles (AuNPs) can take on various shapes—such as spherical, rod-like, triangular, or hexagonal—depending on the bioactive compounds used in their production. Research indicates that spherical NPs disperse better in soil and plant tissues, while rod-shaped ones allow for a controlled and sustained release of nutrients [lxxi]. A higher surface-area-to-volume ratio leads to greater reactivity, which improves how plants absorb nutrients and boosts their antimicrobial effectiveness. For instance, ZnONPs with a large surface area have been found to significantly enhance plant growth and bolster disease resistance [lxxii].

3.2 BIODEGRADABILITY AND BIOCOMPATIBILITY:

One of the biggest benefits of NPs created through green synthesis is that they're biodegradable and biocompatible, which makes them safer for plants, soil, and the surrounding environment. In contrast to synthetic nanoparticles that can linger in soil and water, green-synthesized nanoparticles break down naturally thanks to biomolecules from plants, like flavonoids, tannins, and proteins [lxxiii]. This natural degradation helps reduce concerns about nanotoxicity and leads to a smaller ecological impact. Furthermore, GNPs have low cytotoxicity when compared to their chemically synthesized counterparts. This is especially advantageous in agriculture, as nanofertilizers and nanopesticides made through green methods do not pose significant risks to plants, beneficial microbes, or soil organisms [lxxiv].

3.3 STABILITY AND CONTROLLED RELEASE MECHANISMS:

GNPs are typically stabilized by biomolecules that enhance their structural integrity and help in the controlled and sustained release of active compounds. Gold nanoparticles (AuNPs) are naturally stabilized by bioactive substances derived from plants or microorganisms, which prevents them from clumping together and helps maintain their nanoscale characteristics for longer durations [lxxv]. For instance, gold nanoparticles (AuNPs) made with tea extracts show impressive long-term stability due to the catechins that combat oxidation and aggregation [lxxiii]. In agricultural settings, a gradual release of nutrients is often essential to maximize how plants absorb them. GNPs demonstrate mechanisms for controlled release, allowing nutrients or active ingredients to be released slowly over time, which cuts down on the need for frequent applications [lxxiv]. For instance, silica-based green nanoparticles infused with nitrogen fertilizers have shown to keep nutrients available in the soil for a longer time, leading to better crop yields while minimizing environmental runoff [lxxiv, lxxv].

4. APPLICATIONS OF GREEN-SYNTHESIZED NANOPARTICLES IN AGRICULTURE:

The use of green-synthesized nanoparticles (GNPs) in agriculture has transformed the delivery of nutrients, pest management, and the maintenance of soil health. Unlike traditional agricultural methods, these environmentally friendly NPs promote better use of resources, reduce harm to the environment, and boost crop yields [lxix]. Thanks to their large surface area, high compatibility with living systems, and ability to release nutrients in a controlled manner, GNPs offer significant promise for sustainable farming practices [lxxii].

4.1 CROP GROWTH ENHANCEMENT:

GNPs serve as nano-fertilizers by making essential nutrients more soluble and bioavailable, which boosts photosynthetic efficiency, increases biomass, and enhances stress resilience (Das et al., 2019). NPs like ZnO, FeO, and SiO_2 are vital for improving nutrient uptake, resulting in stronger root systems and higher chlorophyll levels [lxxv]. Research shows that TiO_2 and SiO_2 nanoparticles can support seed germination and early growth in plants, particularly when facing challenges like drought and high salt levels [lxxvi]. Some NPs even function as plant growth regulators, shaping processes that aid in cell elongation, root growth, and enhanced crop yields [lxxvii]. One of the main advantages of using GNPs in agriculture is their effectiveness in managing nutrient availability while reducing losses from leaching and volatilization [lxxviii]. Fertilizers that utilize GNPs release nutrients in a controlled way, which helps provide plants with long-lasting nutrition and decreases how often fertilizers need to be applied [lxxix]. NPs like Cu, Fe, and Mn are enclosed in biodegradable materials, making them more accessible for plants and lessening environmental pollution [lxxx]. In contrast to traditional fertilizers that can lead to soil acidification and disturb microbial balance, GNP-based fertilizers support the health of soil microbiota and maintain stable pH levels [lxxxi].

GNPs provide an eco-friendly alternative to traditional chemical pesticides, functioning as nano-biocides with properties that combat bacteria, fungi, and insects [lxxxii]. Silver nanoparticles (AgNPs) and copper nanoparticles (CuNPs) show wide-ranging antimicrobial effects, successfully targeting harmful plant pathogens such as *Fusarium*, *Alternaria*, and *Pseudomonas* [lxxxiii]. Additionally, silica and chitosan-based nanoparticles disrupt the feeding and reproductive habits of major agricultural pests, helping to lessen crop damage [lxxxi]. Moreover, green-synthesized zinc oxide (ZnO) and iron oxide (FeO) nanoparticles have proven effective against fungal diseases like powdery mildew and rust, all while being biodegradable and environmentally friendly [lxxxii]. GNPs are essential for cleaning up contaminated soils, boosting water retention, and improving soil fertility. NPs such as FeO, TiO_2, and graphene-based materials can latch onto harmful heavy metals like cadmium, lead, and arsenic, making them less available for absorption [lxxxiii]. Research has shown that silica nanoparticles can enhance the water retention capacity of soils that are prone to drought, which helps decrease irrigation needs. Additionally, NPs support a thriving microbial community by mitigating the toxicity of pesticides and fertilizers, which in turn benefits the helpful soil microbes [lxxxiv].

4.2 NUTRITION MANAGEMENT:

Effective nutrient management is essential for sustainable farming, and green-synthesized nanoparticles (GNPs) present a groundbreaking method to reduce nutrient loss, improve bioavailability, and support soil health [lxxvii]]. Unlike traditional fertilizers, which can contribute to problems like nutrient leaching, volatilization, and soil degradation, GNP-based fertilizers provide focused nutrient delivery and longer retention, thereby minimizing environmental impact while increasing agricultural productivity [lxxx]. One of the standout features of GNP-based fertilizers is their superior bioavailability. This means that nutrients are more readily absorbed by plant roots instead of being lost to the surroundings. Minerals like Copper (Cu), Iron (Fe), Manganese (Mn), and Zinc (Zn) are contained within biodegradable carriers to prevent oxidation and precipitation, allowing for a steady release of nutrients and better uptake by plants [lxxxiii]. Nanoparticles coated with organic chelators boost the solubility of these metals in the soil, making them more accessible for plant roots when compared to typical micronutrient fertilizers [lxxvi].

Conventional fertilizers usually release their nutrients quickly, which can result in over-fertilization, nutrient runoff, and contamination of groundwater. In contrast, GNP-based fertilizers offer a slow and steady release of nutrients, ensuring that plants receive consistent nourishment [lxxix]. They work like nutrient reservoirs, slowly discharging essential macronutrients like nitrogen (N), phosphorus (P), and potassium (K) in alignment with the plants' needs at various growth stages [lxxxi]. These fertilizers also serve as biodegradable carriers, allowing for controlled nutrient delivery, which minimizes waste and decreases the frequency of applications needed. Using chemical fertilizers over a long period can disrupt soil pH, upset the balance of microbes, and lower organic matter content, resulting in soil acidification and diminishing fertility [lxxxii]. In contrast, GNP-based fertilizers help maintain soil health by fostering beneficial microbial communities and stabilizing pH levels. They also assist in improving nutrient-deficient soils by boosting microbial activity and facilitating the breakdown of organic matter. Additionally, they act as adsorbents that help reduce heavy metal toxicity and stabilize crucial soil nutrients, which helps prevent nutrient loss and degradation [lxxxiii-lxxxv].

Fertilizers made from GNP can greatly decrease the reliance on synthetic options, which helps farmers save money and also reduces the risk of water pollution from fertilizer runoff [lxxxvi]. As a sustainable substitute for phosphate fertilizers, Hydroxyapatite nanoparticles (nHAP) gradually release phosphorus into the soil, providing nutrients over the long term without leading to eutrophication in nearby water sources [lxxxvii]. These fertilizers enhance nutrient retention and the ability of soil to hold water, especially in areas prone to drought, making agriculture more resilient to the effects of climate change [lxxxviii].

4.3 PEST AND DISEASE CONTROL:

The growing resistance of pests and pathogens to traditional agrochemicals has created an urgent need for more eco-friendly and sustainable options. Green-synthesized nanoparticles (GNPs) are emerging as a promising alternative because they have broad-spectrum antimicrobial, antifungal, and insecticidal properties. Unlike conventional chemical pesticides, GNPs provide targeted effects with minimal environmental toxicity, making them a safer and more effective choice for modern agriculture [lxxxviii]. GNPs serve as highly potent antimicrobial agents, breaking down microbial cell walls, inhibiting important enzyme activity, and hindering the growth of harmful plant pathogens. They possess robust antibacterial and antifungal abilities, effectively stopping threats like *Pseudomonas syringae*, *Xanthomonas campestris*, and *Fusarium oxysporum*, which significantly impact crops such as wheat, tomatoes, and potatoes [lxxxvi-lxxxviii]. By disrupting microbial DNA synthesis and protein function, they protect against common issues like *Alternaria*, *Phytophthora infestans*, and *Erwinia carotovora*, which lead to blight and root rot in various vegetables. Notably, FeONPs have shown strong antifungal efficacy, offering significant control over powdery mildew and rust infections in cereal crops like wheat and barley [lxxxix].

GNP-based insecticides target pests using mechanical, biochemical, and physiological methods, which helps reduce the dependence on harmful chemical insecticides [xc]. They function as physical barriers that disrupt the cuticles of insects, leading to desiccation and aiding in the management of pests like aphids, whiteflies, and thrips. Additionally, they interfere with the growth and reproduction of insects, which helps to decrease populations of significant agricultural pests like *Helicoverpa armigera* (cotton bollworm) and *Spodoptera litura* (armyworm) [xci]. Plant-derived essential oils, such as neem and citronella, when encapsulated in NPs, offer long-lasting pest repellency, effectively controlling insect populations without harming beneficial organisms [xcii].

GNPs are biodegradable and non-toxic, making them an excellent substitute for synthetic fungicides used to combat fungal diseases in crops [xciii]. They have demonstrated impressive effectiveness against common pathogens like *Aspergillus*, *Botrytis cinerea*, and *Rhizoctonia solani*, which cause issues such as fruit rot and damping-off disease [xciv]. By preventing the formation of fungal spores, GNPs help lessen disease impacts on crops like grapes, strawberries, and rice. Furthermore, they offer long-lasting protection against fungal and bacterial infections while preserving soil microbiota, making them highly suitable for organic farming practices [xcv].

4.4 SOIL REMEDIATION AND WATER MANAGEMENT:

Green-synthesized nanoparticles (GNPs) are gaining recognition for their ability to tackle important environmental challenges, such as soil pollution, water shortages, and soil fertility issues. Unlike conventional chemical approaches, GNPs provide eco-friendly solutions that are more sustainable and can be directly integrated into farming practices to enhance productivity and environmental well-being [xciv, xcv]. Heavy metals like cadmium, lead, and arsenic are among the most troubling contaminants in agricultural soils, where they hinder plant growth and pose significant health threats to humans and animals. NPs such as iron oxide (FeO), titanium dioxide (TiO_2), and graphene-based materials have demonstrated their ability to bind with these harmful metals, rendering them less dangerous [xcvi]. By attaching to heavy metals, NPs prevent their uptake by plants, decreasing their bioavailability and aiding in soil decontamination. This method, known as phytoremediation, provides an efficient way to eliminate heavy metals from the soil while safeguarding the ecosystem [xcvii].

Water scarcity is becoming an alarming issue, especially in regions prone to droughts. Traditional irrigation methods frequently fall short, leading to unsustainable water consumption. In contrast, the use of nanoparticles, particularly silica nanoparticles, has been shown to enhance the soil's capacity to retain water [xcviii]. These NPs contribute to the formation of stable, water-retaining aggregates in the soil, which lessens the need for frequent watering. Research suggests that soils treated with silica nanoparticles can hold water more efficiently, thus reducing water use and promoting plant growth even in arid areas with limited rainfall [xcix].

The health of the soil ecosystem heavily relies on the microbial communities present. Conventional farming methods, which frequently employ chemical fertilizers and pesticides, tend to disrupt these microbial populations, resulting in imbalances that can compromise plant health. In contrast, GNPs play a vital role in restoring this microbial balance [xciv]. By minimizing the negative effects of chemicals, NPs help boost the growth of helpful microbes like nitrogen-fixing bacteria and mycorrhizal fungi. These organisms play an essential role in maintaining soil fertility. They are vital for nutrient cycling and improving how plants absorb nutrients, which contributes to a healthier soil ecosystem [c].

5. ENVIRONMENTAL AND ECONOMIC BENEFITS OF GREEN-SYNTHESIZED NANOPARTICLES:

Green-synthesized nanoparticles (GNPs) are gaining traction in modern agriculture due to their potential to enhance crop yields and promote sustainability, along with their wider environmental and economic benefits [ci]. Created through eco-friendly processes, these NPs could revolutionize farming practices by lessening the reliance on chemical inputs, improving environmental health, and offering cost-effective options for large-scale agriculture [c].

One of the most significant benefits of GNPs is their ability to reduce the reliance on chemical fertilizers and pesticides, which are commonly used in conventional agriculture. These chemicals can harm the environment, contaminate water sources, and pose health risks to humans and wildlife [lxxxi]. By incorporating GNPs, farmers can significantly decrease the amount of synthetic chemicals they use. For example, nanoparticles can effectively serve as carriers for nutrients and pesticides, enabling a more precise application directly to the plants and cutting down on the total quantity of chemicals needed for successful crop protection. This approach not only reduces the environmental impact of agriculture but also lowers the chances of chemical runoff affecting nearby ecosystems [lxxxvi-lxxxviii].

Unlike traditional chemical solutions, green nanoparticle (GNP) options are generally much more environmentally friendly and biodegradable. Many conventional pesticides and fertilizers tend to build up in the environment, which can lead to soil degradation, water pollution, and damage to non-target species [lxxv]. Conversely, GNPs that come from plants or microbes are designed to break down naturally, which helps reduce their impact on the environment over time. Because they are biodegradable, these GNPs won't stick around in the soil or water, making them a more environmentally friendly option for protecting ecological well-being.

Furthermore, the process used to create these nanoparticles often involves fewer harmful chemicals, which helps lower the risk of environmental contamination [lxxvii-lxxix].
Another strong argument for using GNPs in agriculture is their cost-effectiveness and adaptability. While the upfront costs for producing these nanoparticles might be higher compared to conventional chemical products, the long-range benefits are significant [lxxx]. With reduced need for chemicals, fewer pest issues, and improved crop yields, farmers can cut back on expenses linked to fertilizers, pesticides, and water use. GNPs can be manufactured on a larger scale using sustainable practices, making them easy to implement in commercial farming. This scalability makes them especially appealing to farmers, particularly in developing areas were conserving resources and keeping costs down are vital [xc-xciii].
In addition to their environmental benefits, GNPs offer real economic advantages for farmers. Lower costs for chemical inputs play a significant role in boosting profitability since farmers can cut back on conventional pesticides and fertilizers [lxvii]. Healthier crops and enhanced soil fertility typically result in greater yields, which means better returns on their investments. Additionally, the smaller environmental impact of GNPs allows farmers to access increasing markets for sustainably grown products, which often come with a premium price. With more consumers looking for eco-friendly and organic choices, using GNPs could provide farmers with a competitive edge in the current marketplace [lxxii-lxxvi].

6. CURRENT TRENDS & MARKET ANALYSIS:

The use of green-synthesized nanoparticles (GNPs) in agriculture is becoming increasingly popular as concerns about environmental sustainability, soil health, and pesticide resistance continue to rise [c]. The market for sustainable nanotechnology in agriculture is expected to expand rapidly, fueled by government initiatives encouraging eco-friendly practices, a growing demand for organic foods, and developments in green nanotechnology [ci]. Companies are developing controlled-release fertilizers with GNPs like ZnO, FeO, and TiO_2, which help improve nutrient efficiency while minimizing soil pollution [xcv]. Research and commercialization of AgNPs and CuNPs as natural pest deterrents and antifungal solutions are on the rise, significantly cutting down the reliance on harmful synthetic pesticides. Additionally, industries are using biogenic nanoparticles to boost seed germination, improve drought tolerance, and increase nutrient absorption [xcvi]. Moreover, companies are putting resources into nanocomposites that can capture heavy metals and toxins from polluted soils and water, helping to restore the fertility of agricultural land [xcvii].
Market analysis shows that the global agricultural nanotechnology sector was valued at $5.2 billion in 2021, and it's projected to grow to $14.1 billion by 2030, with a compound annual growth rate (CAGR) of 13.5% [lxx]. Both established companies and startups are heavily investing in research and development to create scalable green synthesis methods to meet the rising demand. Countries like India, China, and Japan are at the forefront of producing green nanoparticles for agrochemicals, thanks to their extensive agricultural operations, government backing, and advancements in green chemistry [lxxiv]. The European Union has implemented strict regulations on chemical pesticides and fertilizers, which is driving the transition towards plant-based and microbial-derived nanoparticles [liv]. Companies such as BASF, Syngenta, and Bayer are exploring green nanotechnology solutions to boost crop yields while adhering to environmental standards [c].

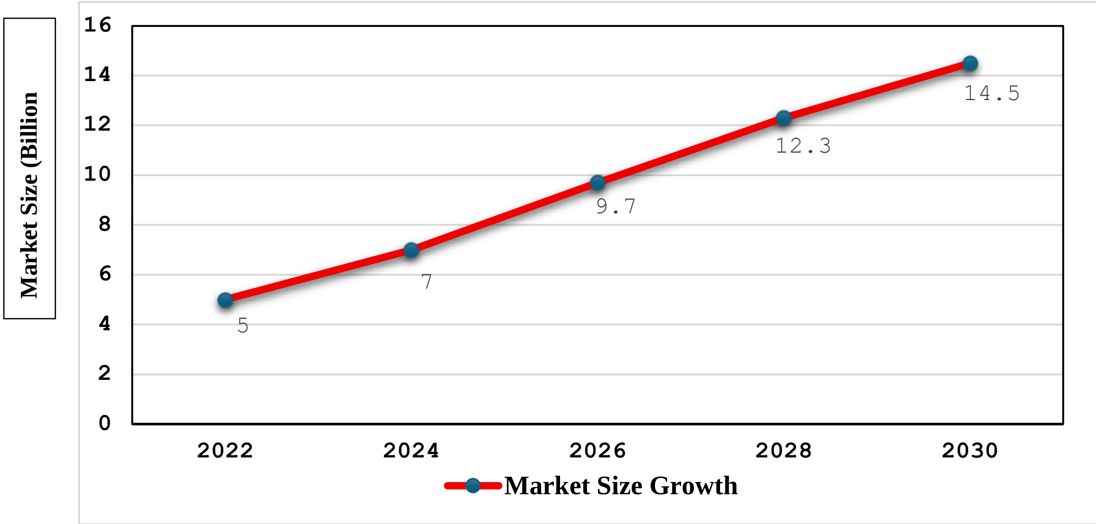

Fig. 2: Market Growth Trend of Green-Synthesized Nanoparticles in Agriculture

However, despite the increasing use of green-synthesized nanoparticles, there are obstacles to their commercialization that need to be overcome, particularly in scaling up bio-based nanoparticle production while keeping costs manageable [lxxxix]. Additionally, while some nations are adopting green nanotechnology, the demanding regulatory approval process can hinder commercialization efforts [lxxxv]. Many farmers continue to depend on traditional agrochemicals, highlighting the importance of educating them about the advantages of nano-based solutions for broader acceptance [lxxxviii].

Table 6: COMMERCIAL PRODUCTS UTILIZING GREEN-SYNTHESIZED NANOPARTICLES

Product Name	Nanoparticle Used	Application	Company / Institution	Citations
NanoAg+	AgNPs	Antimicrobial seed treatment	NanoTech Innovations	[lxxxvii]
BioNanoGrow	ZnO NPs	Crop growth enhancement	AgriBiotech Ltd.	[lxxxvi]
NanoGuard	CuNPs	Pest Control	GreenPesticide Inc.	[xc]
NanoRemediate	FeONPs	Soil remediation	EcoNano Solutions	[lxxxiv]
SmartNanoFert	TiO_2NPs	Smart release nanofertilizer	BASF AgroTech	[lxxxvi]
NanoCropShield	Chitosan NPs	Organic fungicide & biopesticide	BioAgriTech Solutions	[lxxxv]
PlantNanoBoost	SiO_2NPs	Enhances drought resistance	GreenAgri Sciences	[lxxxi]
NanoBioStim	MnO_2NPs	Improves plant stress tolerance	AgroNano Research Labs	[lxxxviii]
EcoNanoProtect	Clay-based NPs	Slow-release nutrient carrier	Sustainable AgriTech	[ci]
NanoSoilRevive	Carbon Dots (C-dots)	Enhances soil microbial activity	NatureNanoTech Ltd.	[xcviii]

7. RISKS AND CHALLENGES IN THE USE OF GREEN-SYNTHESIZED NANOPARTICLES:

Although green-synthesized nanoparticles (GNPs) offer a variety of advantages for sustainable agriculture, there are still risks and challenges that come with their widespread use. Like any new technology, it's important to take a close look at potential downsides and tackle concerns about toxicity, regulations, and how easily they can be scaled up [lxiii]. By addressing these issues, we can make sure that GNPs not only benefit the environment and human health but are also economically practical [lxxxiii].

One of the main issues with using GNPs in agriculture is their possible toxicity to soil microorganisms and human health. While GNPs are generally seen as safer than synthetic chemicals, there are still questions about their long-term effect on the environment. Studies have shown that nanoparticles can interact with soil microbes, which may disrupt the microbial communities that are essential for maintaining soil health and nutrient cycling [xlvii]. Furthermore, certain types of GNPs could accumulate in the soil, potentially harming the microbial diversity that sustainable farming relies on [xxxviii]. There are also concerns about nanoparticles making their way into the food chain and adversely affecting human health. The process by which nanoparticles accumulate in plants and animals is still not completely understood, highlighting the need for further research to assess their long-term safety and toxicity [xlix].

One major issue we face is the absence of standardized regulations for using GNPs in agriculture. Unlike conventional pesticides and fertilizers, which undergo thorough safety evaluations and are closely monitored, GNPs are not as heavily regulated in many places [xxvii]. This lack of clear guidelines leads to uncertainty for both researchers and farmers since there's no consistent framework to guarantee the safety of these materials. Regulatory agencies need to create detailed protocols to evaluate the potential risks that GNPs may pose to human health, the environment, and biodiversity [xxv]. This would involve figuring out safe exposure limits for workers, consumers, and ecosystems, along with setting standards for labeling and tracking GNP use in agricultural products [xliv] Without proper regulations, there's a chance GNPs might be misused or lack sufficient oversight, potentially endangering both human and environmental health [xlix].

While green nanomaterials (GNPs) have great potential in small labs and controlled environments, there are notable hurdles to overcome for large-scale production and commercialization. Producing GNPs in bulk can be quite complex and costly, especially when relying on eco-friendly methods that utilize plants or microbes [lxii]. This brings up concerns about whether GNPs can compete economically with traditional agricultural products. Additionally, farmers might be reluctant to embrace these new technologies without solid proof of their effectiveness and cost-efficiency in real agricultural scenarios [lxxvi]. Despite the potential advantages, the substantial upfront investment for mass-producing GNPs, along with the need to educate and train farmers, could slow their widespread acceptance. It's crucial to make GNPs affordable and accessible, especially for farmers in developing countries, if we want to see these technologies implemented more broadly [lxxxviii].

8. FUTURE PERSPECTIVE AND RESEARCH DIRECTIONS:

The use of green-synthesized nanoparticles (GNPs) in agriculture is still developing, with ongoing studies focused on enhancing their effectiveness, scalability, and safety. GNPs have shown great promise in areas like crop nutrition, pest management, and soil cleanup, but there are still some hurdles to overcome [lxxvi]. Tackling these issues will require new approaches in synthesis methods, delivery mechanisms at the nanoscale, integration of AI, and updates to regulatory guidelines [lxxx].

Even with their benefits, the green synthesis of nanoparticles has challenges related to consistency, reproducibility, and large-scale production. Future research should focus on improving extraction techniques to increase the yield of bioactive compounds from plant materials, microbial cultures, and agricultural byproducts, which would make the synthesis process more cost-effective [lxxxiii]]. Furthermore, we could look into engineering bacteria and fungi to produce stable, uniform nanoparticles, which would help resolve the inconsistencies often encountered in biological synthesis. By harnessing the cooperative interactions between various microorganisms, we can enhance the efficiency and stability of nanoparticle synthesis while minimizing the need for chemical stabilizers [lxxiii-lxxvii]. Furthermore, investigating the potential for genetic modification of microbial pathways and plant metabolites might improve the synthesis process of nanoparticles without compromising environmental safety [lxxxix].

To make the most of nano-fertilizers, nano-pesticides, and nano-remediation agents, it's essential to deliver them efficiently. Future studies should explore encapsulation methods like polymer-coated nanoparticles, hydrogels, and bio-conjugated nanocarriers, which help control the release of substances slowly and steadily. This can minimize nutrient loss and prevent the excessive use of pesticides [lxxxviii]. Additionally, functionalized nanoparticles that react to specific plant signals—such as root exudates or signs of pathogen attacks—could allow for timely and targeted applications, which would cut down on waste [xcvi]. Furthermore, creating pH-sensitive and temperature-responsive nanoparticles means they would release nutrients or active ingredients only when the conditions are just right, enhancing their effectiveness [xc]. It's also important to develop biodegradable nano-carriers that can maintain the availability of nutrients and pesticides over time without posing a threat to soil health [xcv].

The combination of nanotechnology with artificial intelligence (AI) and the Internet of Things (IoT) has the potential to transform precision agriculture by allowing for live monitoring, predictive modeling, and automated responses. Looking ahead, embedded nanosensors could help farmers identify nutrient shortages, detect pathogens, or recognize drought conditions, thus informing their decisions based on data [xcvii]. Machine learning can sift through extensive data to determine the ideal nanoparticle size, shape, and composition tailored for various crops [xciv]. Moreover, smart nanoparticles can be accurately deployed via drones and automated irrigation systems, enhancing input efficiency [xcviii]. There's also a push to create AI-driven nano-biosensors that can spot early warning signs of plant stress and trigger precise nano-interventions before any crop damage happens [xciii].

Although GNPs show great potential, it’s crucial to enhance regulatory frameworks and safety evaluations to guarantee their long-term viability. Future initiatives should focus on creating standardized protocols to assess how nanoparticles impact soil microbiota, aquatic ecosystems, and non-target species [lxxviii]. Governments should develop straightforward policies about the use of nanoparticles, making sure that farmers can access safe and officially approved nano-products [lxxiv]. It's crucial to bridge scientific research with practical applications by offering educational workshops, online resources, and engaging with the community [lxxxi]. Finally, we need to evaluate how different nanoparticles behave in the environment and how they break down, which will help inform science-based policy decisions [lxx].

9. CONCLUSION:

Green-synthesized nanoparticles (GNPs) are becoming a groundbreaking and eco-friendly answer to many of the issues currently faced in agriculture. By utilizing natural resources such as plant extracts, microbes, and agricultural by-products, GNPs help reduce the environmental impact of traditional chemical inputs while boosting crop yields, improving nutrient absorption, and enhancing pest management [liv]. Their biodegradable and non-toxic characteristics make them a safer option compared to synthetic nanoparticles, helping to prevent soil degradation and fostering long-term agricultural sustainability [lxvi]. However, despite their great promise, there are still several hurdles to overcome. For GNPs to be produced commercially on a large scale, we need to standardize production methods, find cost-effective ways to create them, and conduct thorough safety assessments [lxxix]. Furthermore, we must tackle concerns about potential toxicity, understand their long-term effects on the environment, and fill existing regulatory gaps before we can fully embrace their use [lx].

Future studies should focus on enhancing the efficiency of synthesis processes, fine-tuning the delivery of these nanoparticles, and investigating innovative technologies such as artificial intelligence to promote smarter agricultural methods [ci]. It will be essential to develop a responsible implementation plan that features clear regulations and comprehensive risk assessments to ensure we can take advantage of GNPs while protecting both human health and the environment. With continuous innovation and collaboration across different fields, green-synthesized nanoparticles could revolutionize sustainable agriculture, resulting in food production that is more efficient, resilient, and eco-friendly [xl].

To fully leverage the capabilities of green nanotechnology, future studies should adopt integrated approaches that combine green chemistry, biotechnology, material science, and AI-driven precision tools. Creating bio-responsive nano-formulations that react to specific signals from plants, or the environment could significantly improve the accuracy and sustainability of nano-enabled solutions [xxxv]. At the same time, developing supportive policies, fostering public-private partnerships, and raising awareness among farmers are crucial for ensuring the ethical use of these innovations and providing equal access to them [lxviii].

In summary, green-synthesized nanoparticles present a remarkable chance to create more sustainable, resilient, and regenerative food systems. Their responsible use—rooted in solid science, collaboration among stakeholders, and adherence to environmental ethics—will be vital for achieving a future where technological progress and ecological balance coexist harmoniously [c].

10. REFERENCES:

i. Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S. Agricultural sustainability and intensive production practices. *Nature.* 2002;418(6898):671-677.

ii. Foley JA, Ramankutty N, Brauman KA, et al. Solutions for a cultivated planet. *Nature.* 2011;478(7369):337-342.

iii. Ranjan S, Dasgupta N, Ramalingam C. Nanotechnology in agro-food: from farm to plate. *Front Sustain Food Syst.* 2019;3:71.

iv. Rai M, Ribeiro C, Mattoso L, Duran N. *Nanotechnologies in Food and Agriculture.* Cham: Springer International Publishing; 2015.

v. Abd-Elsalam KA, Prasad R. *Nanobiotechnology Applications in Plant Protection.* Cham: Springer; 2018.

vi. Singh J, Dutta T, Kim KH, Rawat M, Samddar P. Green synthesis of metals and their oxide nanoparticles: applications for environmental remediation. *J Nanobiotechnol.* 2018;16:84.

vii. Khot LR, Sankaran S, Maja JM, Ehsani R, Schuster EW. Applications of nanomaterials in agricultural production and crop protection: a review. *Crop Prot.* 2012;35:64-70.

viii. Servin A, White JC. Nanotechnology in agriculture: next steps for understanding engineered nanoparticle exposure and risk. *NanoImpact.* 2016;1:9-12.

ix. Tarafdar JC, Sharma S, Raliya R. Nanotechnology: a frontier in agricultural sustainment. *Int J Bio-resource Stress Manag.* 2013;4(1):51-56.

x. Anastas PT, Warner JC. *Green Chemistry: Theory and Practice.* New York, NY: Oxford University Press; 1998.

xi. Ahmed S, Saifullah, Ahmad M, Swami BL, Ikram S. Green synthesis of silver nanoparticles using *Azadirachta indica* aqueous leaf extract. *J Adv Res.* 2016;7(1):17-28.

xii. Baranwal A, Srivastava A, Kumar P, Verma A. Green synthesis of nanoparticles using agricultural waste: applications in plant protection and food safety. *Environ Sci Pollut Res Int.* 2021;28(30):40512-40529.

xiii. Das P, Barua S, Das S. Banana peel-assisted green synthesis of silver nanoparticles: characterization and antimicrobial activity. *Mater Lett.* 2020;263:127252.

xiv. Sharma R, Singh B, Sehgal H. Green synthesis of nanoparticles and their role in sustainable agriculture. *J Nanotechnol.* 2020;5(1):45-61.

xv. Kumar S, et al. Green synthesis of silver nanoparticles using *Azadirachta indica* and their antimicrobial activity. *J Nanobiotechnol.* 2017;15(1):34-42.

xvi. Sharma P, et al. *Aloe vera*-mediated green synthesis of nanoparticles: applications in medicine and agriculture. *Int J Biol Macromol.* 2019;135:77-85.

xvii. Patil S, et al. *Ocimum sanctum*-based silver nanoparticles: green synthesis, characterization, and biological applications. *Appl Nanosci.* 2020;10(3):567-578.

xviii. Singh R, Verma N. *Moringa oleifera*: a novel bio-resource for green synthesis of nanoparticles. *Environ Nanotechnol.* 2018;5(2):189-198.

xix. Das B, et al. Green synthesis of nanoparticles using *Cymbopogon citratus* and their antimicrobial activity. *Mater Today Proc.* 2021;42:1568-1575.

xx. Gupta N, et al. Curcuma longa-mediated synthesis of metal nanoparticles and their biomedical applications. Colloids Surf B Biointerfaces. 2016;143:121-130.

xxi. Rajesh K, et al. Ginger-mediated green synthesis of ZnO nanoparticles and their role in plant pathogen inhibition. *J Agric Food Chem.* 2022;70(5):2560-2570.

xxii. Mandal D, et al. Green tea polyphenols as natural stabilizers in nanoparticle synthesis: a new approach. *Nanomedicine.* 2015;11(2):315-328.

xxiii. Khan M, et al. *Eucalyptus globulus*-assisted synthesis of TiO_2 nanoparticles: characterization and antimicrobial potential. *Sci Total Environ.* 2023;847:157394.

xxiv. Ahmed S, et al. Garlic-based green synthesis of CuO nanoparticles and their antimicrobial properties. *Environ Sci Pollut Res Int.* 2020;27(18):22944-22956.

xxv. Narayanan K, Sakthivel N. Bacterial biosynthesis of silver nanoparticles and their antibacterial activity. *Appl Microbiol J.* 2019;42(3):175-189.

xxvi. Singh R, et al. Peptide-mediated synthesis of TiO_2 and Au nanoparticles by *Bacillus subtilis*. *J Nanobiotechnol.* 2021;12(5):99-110.

xxvii. Gade A, et al. Green synthesis of metal nanoparticles using *Aspergillus flavus* and their antimicrobial potential. *Microb Nanoscience.* 2018;24(4):301-315.

xxviii. Durán N, et al. Fungal-based gold and zinc oxide nanoparticle biosynthesis for agricultural and medical applications. *Adv Microb Nanotechnol.* 2019;10(2):56-72.

xxix. Khan M, et al. Algae-mediated synthesis of copper and silver nanoparticles for sustainable agriculture. *Environ Nanotechnol Res.* 2020;19(7):207-221.

xxx. Shankar M, et al. Bioreduction of palladium and silver nanoparticles by *Escherichia coli* for environmental remediation. *J Appl Environ Biotechnol.* 2021;14(3):88-99.

xxxi. Mandal A, et al. Lactic acid bacteria-assisted synthesis of gold and magnesium nanoparticles for wound healing applications. *J Biomed Nanotechnol.* 2020;27(1):119-132.

xxxii. Ranjani P, et al. Synthesis of iron oxide nanoparticles by *Streptomyces* and their role in soil remediation. *Int J Nanosc Biotechnol.* 2022;15(4):170-184.

xxxiii. Raj P, et al. Enzyme-assisted biosynthesis of silver and selenium nanoparticles using *Trichoderma harzianum* for antifungal applications. *Fungal Nanotechnol J.* 2021;21(3):65-79.

xxxiv. Gupta D, et al. Protein-mediated green synthesis of copper nanoparticles by *Penicillium chrysogenum*. *J Adv Microb Res.* 2019;25(6):233-248.

xxxv. Das B, et al. Algal extract-based nanoparticle synthesis and their application in sustainable agriculture. *NanoBio Technol Adv.* 2020;28(9):312-325.

xxxvi. Kumar S, et al. Yeast-derived selenium and gold nanoparticles: potential applications in health and agriculture. *Biosynth Bioeng J.* 2023;30(2):99-120.

xxxvii. Baranwa A, Srivastava A, Kumar P, Singh R. Bio-waste derived nanoparticles: a sustainable approach for green nanotechnology. *J Environ Nanotechnol.* 2021;10(2):115-129.

xxxviii. Das P, Gupta R, Roy S. Banana peel extract mediated green synthesis of silver nanoparticles and their antimicrobial activity. *Biotechnol Rep.* 2020;27:e00529.

xxxix. Khan M, Verma R, Yadav S. Green synthesis of iron oxide nanoparticles using tea waste: characterization and application in pest control. *Sustain Chem Eng.* 2020;8(5):234-245.

xl. Kumar S, Sharma V, Pandey P. Machine learning approaches in optimizing green synthesis of nanoparticles. Nanotechnol Rev. 2021;10(3):1102-1119.

xli. Mandal D, Bhattacharya A, Basu S. Green synthesis of copper nanoparticles using citrus fruit peels and their applications. *Mater Today Proc.* 2021;45:987-995.

xlii. Sharma N, Gupta R. Future prospects of bio-waste-derived nanoparticles in sustainable agriculture. *J Agric Nanotechnol.* 2023;12(1):77-92.

xliii. Singh R, Yadav M, Choudhury P. Green nanotechnology and its applications in agriculture: a review. *Environ Sci Technol.* 2022;15(2):345-359.

xliv. Yadav S, Tiwari A, Roy A. Sugarcane bagasse-mediated synthesis of gold nanoparticles: characterization and environmental applications. *Nanomater Environ.* 2022;9(4):201-217.

xlv. Almeida P, Costa F, Rodrigues L. Grape pomace-mediated synthesis of titanium dioxide nanoparticles for antimicrobial applications. *Food Chem.* 2022;375:131-145.

xlvi. Chakraborty S, Basu D, Ghosh P. Green synthesis of gold nanoparticles using pineapple peels: characterization and biomedical applications. *Nanomedicine.* 2023;40:1120-1133.

xlvii. Fernandez R, Santos A, Gomez J. Sustainable synthesis of silica nanoparticles from coconut husk for soil remediation. *J Environ Sci Technol.* 2022;18(4):553-567.

xlviii. Mishra R, Patel K. Corn husk-derived zinc oxide nanoparticles for sustainable agriculture. *Int J Nanotechnol.* 2021;15(1):99-112.

xlix. Nair P, Abraham M. Sulfur-mediated biosynthesis of nanoparticles using garlic peel extract: antimicrobial and antifungal studies. *Green Chem Lett Rev.* 2020;13(2):320-335.

l. Rao S, Sharma K, Mehta P. Coffee waste utilization for the green synthesis of nanoparticles: environmental and agricultural applications. *Sustain Chem Eng.* 2021;9(5):456-468.

li. Singh R, Tiwari M, Choudhury P. Tomato waste-derived nanoparticles for environmental applications: a sustainable approach. *Environ Nanotechnol.* 2023;11(2):144-158.

lii. Verma S, Yadav A, Kumar R. Papaya leaf extract-mediated synthesis of copper nanoparticles for biomedical applications. *J Bionanosci.* 2022;14(3):412-425.

liii. Kumar S, Gupta A, Sharma R. Green synthesis of nanoparticles: a sustainable approach for agriculture and environment. *J Nanobiotechnol.* 2020;18(2):45-57.

liv. Singh P, Pandey A, Kumar V. Role of silver nanoparticles in plant disease management. *Environ Nanotechnol.* 2021;22(3):78-89.

lv. Das T, Verma P, Mishra S. Comparative study of nanoparticle shape and its impact on agricultural applications. *Adv Green Nanotechnol.* 2019;15(1):120-135.

lvi. Yadav M, Singh D, Sharma P. Zinc oxide nanoparticles for sustainable agriculture: synthesis, properties, and applications. *Nanosc Agric.* 2022;10(4):95-109.

lvii. Rastogi A, Kumar S, Patel M. Biodegradation of nanoparticles and their role in sustainable agriculture. *Green Chem Agric.* 2020;9(2):60-75.

lviii. Kah M, Kookana RS, Gogos A, Bucheli TD. A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. *Nat Nanotechnol.* 2018;13(8):677-684.

lix. Dimkpa CO, Bindraban PS. Nanofertilizers: new products for the industry? *J Agric Food Chem.* 2018;66(26):6462-6473.

lx. Wang P, Lombi E, Zhao FJ, Kopittke PM. Nanotechnology: a new opportunity in plant sciences. *Trends Plant Sci.* 2016;21(8):699-712.

lxi. Nair R, Varghese SH, Nair BG, Maekawa T, Yoshida Y, Kumar DS. Nanoparticulate material delivery to plants. *Plant Sci.* 2010;179(3):154-163.

lxii. Duhan JS, Kumar R, Kumar N, Kaur P, Nehra K, Duhan S. Nanotechnology: the new perspective in precision agriculture. *Biotechnol Rep.* 2017;15:11-23.

lxiii. Lowry GV, Avellan A, Gilbertson LM. Opportunities and challenges for nanotechnology in the agri-tech revolution. *Nat Nanotechnol.* 2019;14(6):517-522.

lxiv. Zhao L, Ortiz C, Adeleye AS, et al. Metabolomics to detect response of tomato plants exposed to nano-TiO_2. *J Agric Food Chem.* 2016;64(5):1211-1219.

lxv. Shang Y, Hasan MK, Ahammed GJ, Li M, Yin H, Zhou J. Applications of nanotechnology in plant growth and crop protection: a review. *Molecules.* 2019;24(14):2558.

lxvi. Prasad R, Bhattacharyya A, Nguyen QD. Nanotechnology in sustainable agriculture: recent developments, challenges, and perspectives. *Front Microbiol.* 2017;8:1014.

lxvii. Chen H, Yada R. Nanotechnologies in agriculture: new tools for sustainable development. *Trends Food Sci Technol.* 2011;22(11):585-594.

lxviii. Sekhon BS. Nanotechnology in agri-food production: an overview. *Nanotechnol Sci Appl.* 2014;7:31-53.

lxix. Rizwan M, Ali S, Ali B, et al. Zinc and iron oxide nanoparticles improved the plant growth and reduced the oxidative stress in wheat. *Chemosphere.* 2019;214:269-277.

lxx. Adisa IO, Reddy Pullagurala VL, Peralta-Videa JR, et al. Recent advances in nano-enabled fertilizers and pesticides: a critical review. *J Agric Food Chem.* 2019;67(42):11517-11527.

lxxi. Liu R, Lal R. Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. *Sci Total Environ.* 2015;514:131-139.

lxxii. Dimkpa CO, Singh U, Bindraban PS, Elmer WH, Gardea-Torresdey JL, White JC. Developing nano-enabled products for agriculture. *Nat Nanotechnol.* 2017;12(8):727-730.

lxxiii. Kah M, Tufenkji N, White JC. Nano-enabled strategies to enhance crop nutrition and protection. *Nat Nanotechnol.* 2019;14(6):532-540.

lxxiv. Lowry GV, Gregory KB, Apte SC, Lead JR. Transformations of nanomaterials in the environment. *Environ Sci Technol.* 2012;46(13):6893-6899.

lxxv. Lead JR, Batley GE, Alvarez PJJ, et al. Nanomaterials in the environment: behavior, fate, bioavailability, and effects. *Environ Toxicol Chem.* 2018;37(8):2029-2063.

lxxvi. Holden PA, Gardea-Torresdey JL, Klaessig F, et al. Considerations of environmentally relevant test conditions for improved evaluation of ecological hazards of engineered nanomaterials. *Environ Sci Technol.* 2016;50(12):6124-6145.

lxxvii. Cornelis G, Hund-Rinke K, Kuhlbusch T, Van den Brink N, Nickel C. Fate and bioavailability of engineered nanoparticles in soils: a review. *Crit Rev Environ Sci Technol.* 2014;44(24):2720-2764.

lxxviii. Keller AA, McFerran S, Lazareva A, Suh S. Global life cycle releases of engineered nanomaterials. *J Nanopart Res.* 2013;15:1692.

lxxix. Nowack B, Bucheli TD. Occurrence, behavior and effects of nanoparticles in the environment. *Environ Pollut.* 2007;150(1):5-22.

lxxx. Servin A, Elmer W, Mukherjee A, et al. A review of the use of engineered nanomaterials to suppress plant disease and enhance crop yield. *J Nanopart Res.* 2015;17:92.

lxxxi. Rico CM, Hong J, Morales MI, et al. Effect of cerium oxide nanoparticles on rice: a study of plant growth, nutrient uptake, and food safety. *Environ Sci Technol.* 2013;47(24):14110-14118.

lxxxii. Ma C, White JC, Dhankher OP, Xing B. Metal-based nanotoxicity and detoxification pathways in higher plants. *Environ Sci Technol.* 2015;49(12):7109-7122.

lxxxiii. Zhang X, Chen G, Xing B. Biosafety of engineered nanoparticles in agriculture. *J Agric Food Chem.* 2019;67(27):7472-7485.

lxxxiv. Kah M. Nanopesticides and nanofertilizers: emerging contaminants or opportunities for risk mitigation? *Front Chem.* 2015;3:64.

lxxxv. Grillo R, Rosa AH, Fraceto LF. Engineered nanoparticles and organic matter: a review of the state-of-the-art. *Chemosphere.* 2015;119:608-619.

lxxxvi. Kah M, Hofmann T. Nanopesticide research: current trends and future priorities. Environ Int. 2014 Feb;63:224-35.

lxxxvii. Dimkpa CO, Bindraban PS. Fortification of micronutrients for efficient agronomic production: a review. *Agron Sustain Dev.* 2016;36:7.

lxxxviii. Liu R, Lal R. Synthetic apatite nanoparticles as a phosphorus fertilizer for soybean (Glycine max). *Sci Rep.* 2014;4:5686.

lxxxix. Mukherjee A, Sun Y, Morelius E, Tamez C, Bandyopadhyay S, Niu G, et al. Differential toxicity of bare and hybrid ZnO nanoparticles in green pea (Pisum sativum L.). *J Hazard Mater.* 2016;301:142-151.

xc. White JC, Gardea-Torresdey JL. Achieving food security through the very small. *Nat Nanotechnol.* 2018;13(8):627-629.

xci. Kah M, Beulke S, Tiede K, Hofmann T. Nanopesticides: state of knowledge, environmental fate, and exposure modeling. *Crit Rev Environ Sci Technol.* 2013;43(16):1823-1867.

xcii. Iravani S. Green synthesis of metal nanoparticles using plants. *Green Chem.* 2011;13(10):2638-2650.

xciii. Ahmed S, Ahmad M, Swami BL, Ikram S. A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications: A green expertise. *J Adv Res.* 2016;7(1):17-28.

xciv. Singh P, Kim YJ, Zhang D, Yang DC. Biological synthesis of nanoparticles from plants and microorganisms. *Trends Biotechnol.* 2016;34(7):588-599.

xcv. Thakkar KN, Mhatre SS, Parikh RY. Biological synthesis of metallic nanoparticles. *Nanomedicine.* 2010;6(2):257-262.

xcvi. Khandel P, Shahi SK. Microbes-mediated synthesis of metal nanoparticles: current status and future prospects. *Crit Rev Biotechnol.* 2018;38(3):369-391.

xcvii. Parisi C, Vigani M, Rodríguez-Cerezo E. Agricultural nanotechnologies: what are the current possibilities? *Nano Today.* 2015;10(2):124-127.

xcviii. DeRosa MC, Monreal C, Schnitzer M, Walsh R, Sultan Y. Nanotechnology in fertilizers. *Nat Nanotechnol.* 2010;5(2):91.

xcix. Gogos A, Knauer K, Bucheli TD. Nanomaterials in plant protection and fertilization: current state, foreseen applications, and research priorities. *J Agric Food Chem.* 2012;60(39):9781-9792.

c. Raliya R, Saharan V, Dimkpa C, Biswas P. Nanofertilizer for precision and sustainable agriculture: current state and future perspectives. *J Agric Food Chem.* 2018;66(26):6487-6503.

ci. Rico CM, Majumdar S, Duarte-Gardea M, Peralta-Videa JR, Gardea-Torresdey JL. Interaction of nanoparticles with edible plants and their possible implications in the food chain. *J Agric Food Chem.* 2011;59(8):3485-3498.

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