agriculture

MDPI

Review

A Perspective Review on Green Nanotechnology in Agro-Ecosystems: Opportunities for Sustainable Agricultural Practices & Environmental Remediation

Geeta Bhandari [1,†], Archna Dhasmana [1,†], Parul Chaudhary [2], Sanjay Gupta [1], Saurabh Gangola [3], Ashulekha Gupta [4], Sarvesh Rustagi [5], Sudhir S. Shende [6], Vishnu D. Rajput [6], Tatiana Minkina [6], Sumira Malik [5,7,*] and Petr Slama [8,*]

1 Department of Biosciences, Himalayan School of Biosciences, Swami Rama Himalayan University, Dehradun 248016, Uttarakhand, India
2 Department of Microbiology, College of Basic Sciences and Humanities, G.B. Pant University of Agriculture and Technology, Pantnagar 263145, Uttarakhand, India
3 School of Agriculture, Graphic Era Hill University, Bhimtal Campus, Bhimtal 263136, Uttarakhand, India
4 Department of Management Studies, Graphic Era Deemed to Be University, Dehradun 180004, Uttarakhand, India
5 Department of Food Technology, School of Applied and Life Sciences, Uttaranchal University, Dehradun 248007, Uttarakhand, India
6 Academy of Biology and Biotechnology, Southern Federal University, Rostov-on-Don 34409, Russia
7 Amity Institute of Biotechnology, Amity University Jharkhand, Ranchi 834001, Jharkhand, India
8 Laboratory of Animal Immunology and Biotechnology, Department of Animal Morphology, Physiology and Genetics, Faculty of AgriSciences, Mendel University in Brno, Zemedelska, 613 00 Brno, Czech Republic
* Correspondence: smalik@rnc.amity.edu (S.M.); petr.slama@mendelu.cz (P.S.)
† These authors contributed equally to this work.

Citation: Bhandari, G.; Dhasmana, A.; Chaudhary, P.; Gupta, S.; Gangola, S.; Gupta, A.; Rustagi, S.; Shende, S.S.; Rajput, V.D.; Minkina, T.; et al. A Perspective Review on Green Nanotechnology in Agro-Ecosystems: Opportunities for Sustainable Agricultural Practices & Environmental Remediation. *Agriculture* **2023**, *13*, 668. https://doi.org/10.3390/agriculture13030668

Academic Editor: Bin Gao

Received: 8 February 2023
Revised: 6 March 2023
Accepted: 9 March 2023
Published: 13 March 2023

Abstract: The modern agricultural system is facing the unprecedented task of contriving the extensive demand for agrarian production owing to population explosion and global climate change. The employment of Nanotechnology in agriculture has gained immense interest in recent times for the development of sustainable agricultural technologies and environmental remediation strategies. Nanotechnology pertains to the employment of nanoparticles and furnishes the potential to fabricate novel materials and products possessing improved quality. The nanomaterials may be used as; nanosensors, nanocides, nanofertilizers, nanobarcodes, and nano-remediators, which play a significant role in modern agricultural practices. However, the physical and chemical processes of nanoparticle production is neither economical nor environmentally sustainable. Therefore, the need for green or biogenic nanoparticles obtained from plants, bacteria, fungi or their metabolites has emerged as novel, sustainable, economical, biocompatible, and eco-friendly technology. In this perspective, the production and sources of biogenic nanoparticles and their implication in agro-ecosystems for crop productivity, soil health management, biocontrol, and environmental remediation have been focused on in this review. The potential development and implementation challenges are also explored.

Keywords: green nanotechnology; green nanoparticles; biogenic nanoparticles; agriculture; environmental remediation

1. Introduction

Rapid population growth, extensive rise in anthropogenic activities, and global climate change have resulted in a wide range of contaminants in different environmental matrices and stress-related degradation of soil quality, leading to preponderate decline in crop productivity across the globe [1]. Abiotic stress is amongst the most alarming issue that is gravely endangering ecosystem stability at a rapid pace [2]. The most prevalent abiotic factors affecting agricultural productivity include salinity, drought, heat, chilling, and heavy metal toxicity. Various ecologically friendly strategies are being employed to limit the detrimental impact of abiotic stressors and promoting plant stress adaption ability, and dealing with the global issue of environmental pollution. Nanotechnology is a multidomain area covering; chemistry, engineering, biotechnology, microbiology, and physics that function for committed development, enhancement, and use of nanoscale (1–100 nm) structures [3]. Owing to their minute size and high surface area to volume ratio, nanoparticles (NPs) exhibit novel properties differentiating them from bulk materials, such as physical strength, stability, optical characteristics, reactivity, electrical conductance, and magnetic properties [4]. Therefore, NPs are employed in diverse fields' consisting; pharmaceutics, cosmetics, health care, biomedical, textiles, food, optics, electronics, sensors, optical devices, electrochemistry, energy, and agriculture. Nanotechnology has the capacity to revolutionize the agricultural and biomedical sectors by the employment of biosensors, nutraceuticals, genetically modified plants and animals, plant growth regulators/promoters, intelligent drug delivery systems, nanoherbicides, nanopesticides, and nanofertilizers [3].

The chemical and physical techniques utilized to synthesize NPs include; irradiation, sonication, pyrolysis, laser ablation, and arc discharge. The chemical methods use hazardous reducing compounds, sodium borohydrate and hydrazine, and result in the production of toxic by-products [5]. The combined energy and capital requirements of these technologies, along with the use of hazardous compounds, nonpolar solvents, synthetic additives, and capping agents, therefore limiting their use in clinical, biomedical, food, environmental, and agricultural applications [2]. Therefore, the hunt for a safe, dependable, nontoxic, and environmentally acceptable method to create NPs has led researchers to focus on "green" chemistry and bioprocesses [6]. Plants parts (seed, flower, leaf, bark, peel), bacteria, fungi, actinomycetes, yeast, viruses, and enzymes have been investigated for developing stable and homogeneous NP synthesizing agents at physiological pH, temperature, and pressure in a clean, environmentally sustainable manner. These organisms are prospective biofactories for NP synthesis since they possess the inherent capacity to biosynthesize NPs in intracellular or extracellular environment [7]. Amino acids, peptides, protein, polysaccharides, tannins, flavonoids, phenols, and vitamins are important reducing and capping agents in biological synthesis and are vital for controlling the size and shape of NPs. The biogenic NP possesses high polydispersity, dimension, and stability. Numerous reports on the applications of biogenic NP in biomedical and clinical sectors are available, however very few studies describe their applicability in the agriculture and environmental sectors [8,9]. The present review provides a comprehensive insight of the different approaches for biogenic synthesis of NP from different sources and their characterization methods. Additionally, the possible applications of these biogenic NPs for enhancing crop productivity, alleviating abiotic stress, and remediation of environmental pollution are discussed. Moreover, the limitations of biogenic NP synthesis, toxicity, and perspective for commercialization have also been discussed.

2. Biogenic Nanoparticles and Their Synthesis

Different chemical methods have been employed for the synthesis of NPs from a wide range of sources. However, in recent times, the inclination towards "green" technologies employing low-cost, renewable, and eco-friendly materials has been observed. The methods of NP synthesis are categorized into top-down and bottom-up approaches (Figure 1). Nanocomposites are synthesized by decreasing the size of macroscopic materials for the subsequent production of aggregates of desirable sizes [10]. The bottom-up methods build nanoscale structures from atomic and molecular materials by chemical, physical, and biological processes.

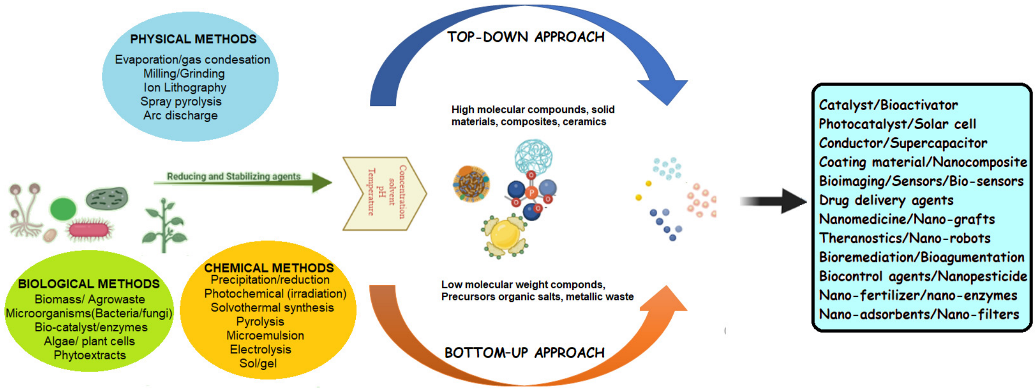

Figure 1. Schematic representation of the synthesis of nanoparticles by top-down and bottom-up approaches and their applications.

2.1. Conventional Synthesis Method

The physical and chemical methods are used in a conventional approach. The top-down method consists of physical processes such as arc discharge, irradiation, ultrasonication, pyrolysis, laser ablation, thermal degradation, and pyrolysis. The physical methods employ mechanical pressure, energy, evaporation, and condensation for NP synthesis. However, the polydisperse nature of the synthesized material, production of defects, contamination due to raw materials while milling, higher energy demand, use of radiation, high temperature, high cost, and complex instrument requirement limit these methods [11].

The chemical method includes electrochemical and sol-gel processes, vapor flux condensation, hydrothermal deposition, microemulsion milling, chemical vapor deposition, and chemical reduction [10]. These methods are cost effective, highly productive, and less dispersed but employ sodium borohydride and sodium citrate as reducing agents that, although enhance reactivity, are highly toxic and have deleterious impact on the ecosystem [7].

2.2. Green Synthesis Method

The chemical and physical methods result in the degradation of chemical groups, production of toxic by-products, and have high energy demand [10]. Therefore, "green nanotechnology" based on biological machinery for the synthesizing biogenic NPs has been explored recently in a bottom-up approach. Synthesis of bio-based nanomaterials such as nanorods, nanotubes, nanoparticles, and nanowires has been economically evaluated as a valuable alternative to fabricating NPs for diverse applications [2,7]. Green synthesis uses biological sources, including plant parts, algae, bacteria, fungus, and biological waste as reducing agents in "bionanofactories" for creating biocompatible nanocomposites through the reduction of metal ions from solutions in a low-energy procedure. Biomolecules are capable of reducing metal ions to uncharged atoms, that, on collision, form stable nuclei through the nucleation process with subsequent repetition of the nucleation to form large particles. Thereafter, stabilization occurs through the coating of the synthesized particles by the different biomolecules. This prevents the accumulation and disruption of biomaterial formation and color changes associated with the metal compounds employed [12]. The intracellular mechanism of biogenic NP synthesis involves the formation of nanoclusters after diffusion of NP into the cell wall, enzymatic bioreduction of metal ions within the cell, and entrapment of positively charged metal ions with negatively charged groups on the cell wall. While the extracellular mechanism of biogenic NP synthesis includes the formation of NP within the cell-free supernatant and enzymatic bioreduction by extracellular enzymes [7]. Green practices are thus ecologically sustainable, cost-effective, efficient, structured exclusively, have high metal uptake capability, require less time, are simple, biocompatible, and suitable for large-scale production [13].

2.3. Nanoparticle Synthesis by Bacteria

In the microbial-mediated synthesis process, bacterial culture filtrate is employed as a reductant for NP fabrication. Various genera of bacteria have been used previously for NP synthesis; *Pyrobaculum*, *Aeromonas*, *Escherichia*, *Burkholderia*, *Stenotrophomonas*, *Bacillus*, *Klebsiella*, *Bhargavaea*, *Weissella*, *Brevibacterium*, *Corynebacterium*, *Desulfovibrio*, *Enterobacter*, *Halomonas*, *Lactobacillus*, *Listeria*, *Pseudomonas*, *Plectonemaboryanum*, *Rhodobacter*, *Rhodococcus, Rhodopseudomonas*, *Sphingobacterium*, *Streptomyces*, *Shewanella*, *Staphylococcus*, and *Weissella* [14,15] (Table 1). Microorganisms can synthesize nanomineral crystals, magnetic oxide metals, and nanoparticles extracellularly or intracellularly [16] (Figure 2). The anionic functional groups on the cell wall play a vital function, by electrostatically interacting with cationic metal ions during intracellular NP synthesis. Subsequently, the metal ions are transported inside the cell by ion transporters for enzymatic reduction intracellularly [7]. However, these NPs are synthesized in low quantity and are localized to specific regions, making them difficult to extract. The extracellular production consists of metal entrapment on cellular surfaces with a subsequent reduction to NPs by several membrane bound enzyme. These NPs are synthesized in high quantity and easier to procure for their intended purposes, but are of polydisperse nature and need to be decreased to the monodisperse level for popularizing the extracellular synthesis [10].

The biochemical processes of microbial-mediated NP synthesis include solubility, adsorption, accumulation, precipitation, toxicity, and efflux [10]. These methods activate the microbial resistance mechanisms for enzyme-mediated cellular detoxification of inorganic particles. Cellular transporters and oxidoreductases, such as nitrate reductase and sulfite reductase, are the major types of enzymes involved [15]. Early reports suggest that NADH/NADPH-dependent nitrate reductases are significant in microbial-mediated metal NP biosynthesis [17]. *Bacillus licheniformis* synthesizes NADH-dependent nitrate reductase for reducing silver ions to silver NPs [15]. Bacteria convert selenate into red allotropes of Se^0 by selenate and selenite reductases, generally visualized as SeNPs [18]. The charge capping in *Stenotrophomonas maltophilia* in an NADPH-dependent reductase enzyme-assisted process results in the conversion of Au^{3+} to Au^0 for the synthesis of Au-NPs [19]. Intracellular synthesis of AgNPs occurs by the transportation of Ag ions in cells by electrostatic interactions between cationic Ag ions and anionic (carboxyl) groups, and subsequent reduction by enzymes and other metabolites [8]. The extracellular reduction of Ag ions to AgNPs occurs by the excretion of NADH-dependent reductases and sulfur-consisting proteins into the environment. Ag-NPs are synthesized from cell-free extracts of *Bacillus paralicheniformis*, *Bacillus pumilus*, and *Sphingomonaspaucimobilis* [20]. The enzyme reductase and the bioactive metabolic peptide assistin stabilize the Ag- NP. Furthermore, the AgNPs functioned as a nanocatalyst and displayed up to 90% efficacy for the removal of malachite green from contaminated wastewater [20]. The culture filtrate of two plant growth-promoting bacterial strains, *Serratia marcescens* and *Burkholderia cepacia*, were used to prepare biogenic silver NPs and were further employed as biocontrol agents against phytopathogenic fungi [14]. Both magnetotactic and non-magnetotactic bacteria biosynthesize magnetosomes, which are organically coated iron oxide and iron sulfide nanocrystals, and are capable of producing magnetic radicals. Magnetosomes can be applied for cancer treatment, imaging, and are toxicity-monitoring biosensors [15].

In the presence of a higher concentration of heavy metals, microbes generally respond by expressing certain heavy metal resistance genes for NP production. Microbes employ enzymatic reduction, precipitation, complexation, dissimilatory oxidation, and transport vie efflux systems to survive in high metal concentrations. A two-component signal transduction system, BaeSR, is involved in elevated expression of efflux pumps related to metal resistance [21]. Similarly, an efflux system of *E. coli*, CusCFBA, is over-expressed in the presence of high Copper ions [22]. Researchers have suggested the involvement of conductive pili and cell surface proteins in the transfer of electrons for subsequent extracellular reduction of metal ions [21]. Shi et al. [23] hypothesized that Cym A (an inner membrane c-type cytochromes) oxidizes the quinol pool and transfers the electron to Mtr

A (c-Cyt), which subsequently transfers these electrons to outer membrane c-cytochromes, MtrC and OmcA. Furthermore, MtrC and OmcA act as terminal reducing agents and reduce Fe(III) oxides for subsequent NP synthesis. Multiheme complexes assist in electron transfer from the inner membrane to the cell surface through periplasm. Additionally, bacterial exopolysaccharides that are excreted extracellularly have also been suggested to function as reducing and capping agents for extracellular synthesis of biogenic NP [21].

Microbes are widely present in the environment, easily cultivable, and show high adaptability in different habitats, making them potent candidates for NP production. However, there are some setbacks of microbial-mediated NP synthesis, such as purification of NP and regulation of geometry owing to limited understanding of biosynthetic mechanisms and scalability. It is difficult to regulate the particle shape and size and produce monodisperse [7]. Thus, further understanding of the biosynthetic mechanisms is required prior to consideration for industrial uses.

Table 1. Biogenic synthesis of NPs from different bacterial species.

Bacterial Strain	Biogenic Nanoparticles	Size and Shape	Localization	Reference
Jeotgalicoccus coquina ZC15	Platinum	5.74 nm, Spherical	Extracellular	[24]
Kocuria rosea MN23	Platinum	5.85 nm, Spherical	Extracellular	[24]
Pseudomonas kunmingensis ADR19	Platinum	3.95 nm, Spherical	Extracellular	[24]
Pseudomonas putida KT2440	Platinum	8.06 nm, Spherical	Extracellular	[24]
Psychrobacter faecalis FZC6	Platinum	2.49 nm, Spherical	Extracellular	[24]
Sporosarcina psychrophila KC19	Platinum	4.24 nm, Spherical	Extracellular	[24]
Vibrio fischeri B11177	Platinum	3.84 nm, Spherical	Extracellular	[24]
Bacillus pumilus, Bacillus paralicheniformis and *Sphingomonas paucimobilis.*	Silver	4–20 nm, Spherical to oval	Extracellular	[20]
Bacillus cereus	Silver	5–7.06 nm, Spherical	Extracellular	[24]
Bacillus pumilus, Bacillus persicus, and Bacillus licheniformis	Silver	77–92 nm, Triangular, hexagonal, and spherica	Extracellular	[25]
Bacillus subtilis KMS2–2	Silver	18–100 nm, Spherical	Extracellular	[26]
Sporosarcina koreensis DC4	Silver and Gold	30–50 nm, Spherical	Extracellular	[27]
Paracoccus haeundaensis BC74171^{T}	Gold	20.93 ± 3.46 nm, Spherical	Extracellular	[6]
Bacillus subtilis	Zinc	10–15 nm, Spherical	Extracellular	[28]
Bacillus Subtilis	Zinc	16–20 nm, Spherical	Extracellular	[29]
Bacillus sp.	Selenium	2–50 nm, Spherical	Extracellular	[30]
Azospirillum brasilense	Selenium	2–50 nm, Spherical	Extracellular	[31]
Streptomyces zaomyceticus Oc−5 and Streptomyces pseudogriseolus Acv−11	Copper	78–80.0 nm, spherical	Extracellular	[32]
Escherichia sp	Copper	22.33 to 39 nm, Spherical	Extracellular	[33]

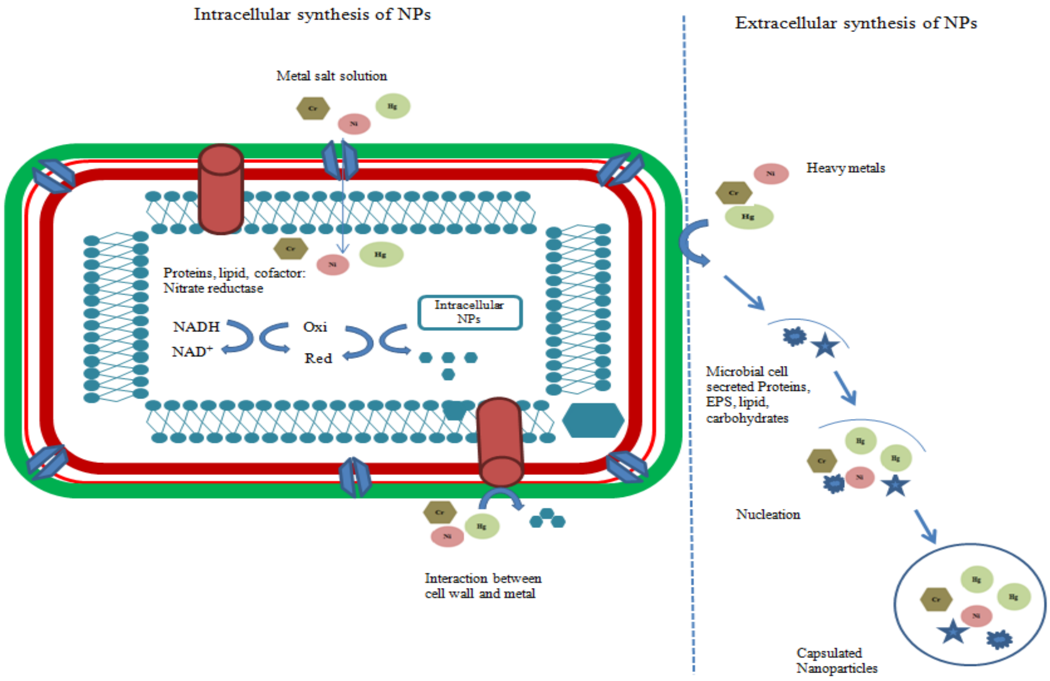

Figure 2. Microbial-mediated biosynthesis of biogenic NPs through intracellular and extracellular modes.

2.4. Nanoparticle Synthesis by Fungi

Fungi synthesize a range of enzymes (acetyl xylan esterase, D- glucosidase, cellobiohydrolase, nitrate reductase), peptides, and quinines (naphthoquinones and ansaquinones) that are involved in the conversion of bulk materials into NPs. The amide groups and amino acids with -SH groups are found to undergo a dehydrogenation reaction with metal salts, such as silver nitrate, to form AgNPs [34]. The fungal enzymes, NADH-dependent nitrate reductase and hydrogenase, reduce Ag to Ag-NPs and Pt^{+2} to Pt^0, respectively [17]. Phenol oxidases (Mn-peroxidase, laccase, and tyrosinase) reported from xylotrophic fungi are also associated with the oxidoreductase system for NP synthesis [35]. Several fungal genera such as *Aspergillus*, *Candida*, *Fusarium*, *Pleurotus*, *Trichoderma*, *Phomopsis*, *Phoma*, *Penicillium*, *Phanerochaete*, and *Verticillium* assist in metal NP synthesis [36]. Ag-NPs were bio-synthesized from $AgNO_3$ by *Ganoderma enigmaticum* and *Trametes ljubarskyi* at 28 °C [37] (Table 2). Jalal et al. [35] reported extracellular biogenic Ag-NPs synthesized from *Candida glabrata*. Biogenic ZnO and CoO NP were reported by Kalpana et al. [36] and Vijayanandan and Balakrishnan [38] from *Aspergillus niger* and *Aspergillus nidulans*, respectively. In comparison to microbial-mediated NP biosynthesis, the fungal-assisted synthesis confers several benefits owing to the occurrence of mycelia, large surface area, higher tolerance to metals, easy reduction of metal ions, easier cultivation, high growth rate, easy control of biomass, cost effective biomass generation, higher enzyme biosynthetic rate for metabolic pathways, and comparatively simpler extraction. Fungal hyphae aggregates can withstand greater amounts of agitation and pressure and thus, can be employed for large-scale NP biosynthesis [15].

Table 2. Biogenic synthesis of Nanoparticles from fungi and algae and their applications.

Organism	Biogenic Nanoparticles	Size and Shape	Applications	References
		Fungi		
Verticillium	Gold	20 nm, Spherical Both extracellular and Intracellular	Catalysis and precursors for synthesis of coatings for electronic applications	[39]
Trichoderma asperellum	Silver	13–18 nm, Spherical	–	[34]
Macrophomina phaseolina.	Silver	5–30 nm, Spherical	Bactericidal for phytopathogens and seed protection agent	[40]
Alternaria sp.	Silver	3–10 nm, Spherical	Biocontrol agent	[41]
Trichoderma harzianum	Silver, Iron and Titanium	15–20 nm, Spherical	Biocontrol agent of *Sclerotinia sclerotiorum*, heavy metal absorption	[42]
Penicillium sp. 8L2	Silver	2–9 nm, Spherical	Biosorption of heavy metal, Biocidal agents	[43]
Candida glabrata	Silver	2–15 nm, Spherical	Antimicrobial agent	[35]
Aspergillus niger	Zinc	41 nm, Spherical	Dye Decolorizing and antimicrobial agent	[36]
Aspergillus niger BSC−1	Iron	20–40 nm, Spherical	Removal of Chromium from aqueous solution	[44]
Trichoderma asperellum, Phialemoniopsis ocularis and Fusarium incarnatum	Iron	13–30 nm, Spherical	Chemosorption of Chromium	[45]
Aspergillus terreus S1	Magnesium	≤38 nm	Precipitation and adsorption	[46]
Ganoderma enigmaticum and Trametes ljubarskyi	Silver	5–40 nm, Spherical	Cytotoxic agents	[37]
Aspergillus nidulans	Cobalt	20.29 nm, Spherical	Energy storgae	[38]
		Algae		
Prasiola crispa	Gold	5–25 nm, Spherical	Nanosensor, Nano-catalyst	[47]
Tetraselmis kochinensis	Gold	5–35 nm, Spherical, Intracellular synthesis	Nano-catalyst	[48]
Scenedesmus−24	Cadmium sulphide	120–175 nm oval, Intracellular synthesis	Heavy metal sequesteration	[49]
Chlorococcum sp. MM11	Iron	20–50 nm, spherical	Chromium remedaition	[50]
Chlamydomonas reinhardtii	Cadmium sulphide	5 nm, Spherical	Photocatalytic degradation agent	[51]
Spirulina plantesis	Palladium	10–20 nm, Spherical	Adsorption of heavy metal	[52]
Ulvan	Silver	33 nm	Bactericidal	[53]
Turbinaria ornata	Zinc oxide	-	Alleviation zinc deficiency and improved the agronomical parameters of maize seedling	[54]
Gelidium corneum	Silver	20–50 nm	Antibiofilm and antimicrobial agent	[55]
Padina pavonia	Silver	49.58–86.37 nm, Variable shape	–	[56]

2.5. Nanoparticle Synthesis by Algae

Though still in its infancy, phyconanotechnology has emerged as a promising field for the synthesis of NPs from algae in recent times. Algae synthesize different types of secondary metabolites, enzymes, pigments, and proteins that can operate as biofactories for NP biosynthesis. Algae such as *Botrycoccus*, *Corallina*, *Cystoseira*, *Dictyota*, *Ecklonia*, *Fucuss*, *Gracilaria*, *Gelidium*, *Padina*, *Sargassum*, *Stereospermum*, and *Ulva* have been reported for green synthesis of NPs (Table 2). Ag-NPs produced by *Ulva lactuca* were subsequently applied as a photocatalyst for the removal of methyl orange [57]. The FT-IR data of synthesized NPs suggested the involvement of bioactive components, phenolics, amines, and aromatic rings as capping and stabilizing agents in NP synthesis [57]. The capability of algae to assist in the biosynthesis of NPs is due to active components (alginate and laminarin) in algal cell walls. Ozturk et al. [55] suggested that Ag^+ ions bind readily to the hydroxyl and carbonyl group of proteins and other biomolecules in *Gelidium corneum* extracts with subsequent reduction to Ag^0. Abdel-Raouf et al. [56] proposed that flavonoids such as catechin, epigallocatechin, epicatechin, epigallo-catechin gallate, and gallic acid obtained from brown algae *Padina pavonia* are capable of reducing and stabilizing Ag^+ ions for the synthesis of Ag-NPs. Recently, ulvan, a novel sulfated polysaccharide, was reported from a green algae *Ulva armoricana* and was assessed for its capability to stabilize and reduce metal ions for the biosynthesis of Ag-NPs [53]. Ulvan can be used as a potential alternative of citric acid, due to its inherent stabilizing capability for AgNPs synthesis. Moreover, it can function as an advanced material for preparing antimicrobial agents for pharmaceutical purposes [53]. The screening of biocatalysts, enzyme activity, and appropriate growth conditions are vital for high-quality NP synthesis. Amongst all microbial systems, algae also enable multi-purpose applications for NP biosynthesis with the additional employment in wastewater treatment, bioenergy, and valuable compounds (pigments, pharmaceuticals) production.

2.6. Nanoparticle Synthesis by Plants

Although the biogenic NP synthesis is an alternative approach to conventional methods and a wide range of NPs have been synthesized from different micro-flora, there are some drawbacks. These include production cost, sample error, and subservient bulk production [15]. Thus, many studies are ongoing on the employment of plants and their biomass for the fabrication of NPs. The bark, fruit, leaf, latex, peel, seed, stem, shoot, root, phytochemicals, and essential oils are an abundant source of proteins, carbohydrates, enzymes, vitamins, organic acids, flavonoids, phenols, polyphenols, tannins, and terpenoids [1]. Different plant varieties including *Achillea wilhelmsii*, *Aloe Vera*, *Azadirachta indica*, *Capsicum annuum*, *Calendula officinalis*, *Camellia sinensis*, *Cinnamomum camphora*, *Coriandrum sativum*, *Cymbopogon flexuosus*, *Datura metel*, *Gardenia jasminoides*, *Gliricidia sepium*, *Ipomoea digitata*, *Jatropha curcas*, *Mentha piperita*, *Moringa oleifera*, *Paullinia pinnata*, *Pelargonium graveolens*, *Piper sarmentosum*, *Rosa* sp., *Tagetes* sp., *Tamarindus indica*, *Terminalia chebula*, and *Zingiber officinale* are being employed to fabricate NPs (Table 3). Phytocompounds catalyze the reduction of metal ions to generate zero valent metal ions that result in aggregation to produce metal NPs [15]. The synthesis and stabilization of Ag-NP from cumin occurs through the oxidation of phenolic groups to generate unstable phenoxy radicals which are resonance-stabilized by electronic rearrangements with subsequent reduction of Ag^+ ions and preventing of Ag^0 nuclei from aggregation [58]. Ahmad et al. [59] reported that hydrogen generated from the keto-enol tautomerization of flavonoids (luteolin and rosmarinic acid) is primarily involved in reducing metal ions to their respective NPs. Polyphenols in *Croton caudatus* extract function as reductants for Au and the synthesized AuNPs possess higher free radical scavenging properties [60]. Plant extracts containing rich quantities of phytocompounds can be used as bioreductors, stabilizing agents, and bioactivators for effective compression and entrapment for extracellular NP production. However, since different plant species contain differing amounts of active, reducing compounds, their reduction capability can be modified, fundamentally influencing the NP synthesis. Furthermore, the concentration of plant extracts (active phytocompounds), time, pH, and the calcination temperature affect the NP synthesis.

Table 3. Biogenic nanoparticles synthesis from different plant sources and their applications.

Biogenic Nanoparticles	Plant Source	Size and Shape	Applications	References
Silver	*Plukenetia volubilis* L.	4–25 nm, Spherical	Photocatalytic degradation and Antioxidant agent	[61]
	Ziziphus jujuba	20–30 nm	Nano-catalyst	[62]
	Biophytum sensitivum	19.06 nm, Spherical	Dye degradation	[63]
	Ocimum basilicum	26.3 to 83 nm, Spherical	Biocontrol agents for Viral infections (Cucumber mosaic virus)	[5]
	Euphorbia granulata	5–20 nm, Spherical	Antioxidant agent, Nano-catalyst	[64]
	Taraxacum officinale	~15 nm, Spherical	Biocontrol agent	[15]
Gold	*Camellia japonica*	40 nm, Spherical and triangular	Antimicrobial agents, Nano-catalyst	[65]
	Aerva lanata	~18 nm, Spherical	Nano-catalyst	[63]
	Eucommia ulmoides	16.4 nm, Spherical	Dye degradation	[66]
Copper	*Theobroma cacao* L.	Spherical, $\leq$32 nm	Nano-catalyst	[67]
	Plant based Starch	50 nm, Spherical clusters	Biosensor	[68]
	Plukenetia volubilis L.	6–10 nm, Spherical	Photocatalytic degradation agent	[69]
Iron	*Mentha spicata* L.	20–45 nm, Spherical	Removal of Arsenic (III&V) from contaminated water bodies	[70]
	Eucalyptus sp.	20–80 nm, Spherical	Treatment of swine wastewater	[71]
	Syzygium cumini	9–20 nm, Spherical	Biomedical	[72]
Zinc oxide	*Physalis alkekengi* L.	72.5 nm, Spherical	Phytoremediation	[73]
	Artocarpus gomenzianus	5–15nm, Spherical	Photocatalytic degradation agent	[74]
	Mentha spicata	11–88 nm, Spherical	Biocontrol agent against Tobacco mosaic virus	[75]
Magnesium oxide	*Acacia gum*	$\leq$100 nm, Spherical	Heavy metal removal	[76]
Lead	*Theobroma cacao*	40 nm, Spherical	Nano-catalyst	[67]
Chitosan/Dextran	*Nicotiana glutinosa*	91.68 nm, Spherical	Biocontrol agent against Alfalfa Mosaic Virus	[77]

3. Characterization of Biogenic Nanoparticles

The size and physico-chemical parameters of NPs are closely related and are crucial for understanding the chemo-physical structure and matrix composition of these materials. Nanoparticle characterization is performed by techniques such as scanning and transmission electron microscopy (SEM, TEM), atomic force microscopy (AFM), dynamic mechanical analysis (DMA), fourier transform infrared spectroscopy (FTIR), X-ray photoelectron spectroscopy (XPS), vibrating-sample magnetometer (VSM), superconducting quantum interference device (SQUID), dynamic light scattering (DLS), NP tracking and analysis (NTA), X-ray powder diffraction (XRD), and UV-Vis spectroscopy [78] (Figure 3). These methods are employed for analyzing parameters such as particle size, pore size, orientation, fractal dimension, dispersion, shape, crystallinity, intercalation, and surface area of nanocomposites [79].

FTIR is used to detect organic functional groups (hydroxyl, carbonyl etc) present on the surface of NPs, while XRD allows the determination of crystal structure and phase identification [80]. The composition, bonding, surface charge, phase, functionalization, chemical state, crystallinity, polarity, and electrochemical nature of NPs can be characterized by these methods [81]. Balasubramanian et al. [82] analyzed biogenic AuNPs synthesized from *Jasminum auriculatum* leaf extract by FTIR and reported a positive shift in the amine, hydroxyl, and amide groups following NP synthesis. The authors also correlated the emergence of two new peaks of nitro groups derived from amide/amine groups and carboxyl groups due to alcoholic residues in the synthesis of AuNPs with the reduction of Au^{3+} to Au^{0}. The FTIR analysis also suggested that flavonoids and alkaloids of plant extracts may be involved in NP synthesis and flavonoids, polyalcohols, and terpenoids may be responsible for their stabilization [82]. Nanocomposite formation is verified by using UV-Vis spectroscopy. By displaying the surface plasmon resonance and energy-dispersive spectroscopy, it determines the elemental make up of NPs. TEM, SEM, and AFM are used for analyzing the size, surface morphology, localization, surface area, shape, dispersity, aggregation, surface area, and porosity. While SEM enables the analysis of size, shape, aggregation, and dispersion of NP, TEM allows the determination of size, shape, localization, dispersity, and aggregation of NPs in two dimensions [83]. According to TEM images, the biogenic selenium and tellurium NPs synthesized from *Aureobasidium pullulans* had spherical shape, however, the Te-NPs were grouped in clusters and the Se-NPs showed random distribution [84]. The authors suggested that clustering may be due to electrostatic interactions of groups of proteins and polysaccharides present in extracellular polymeric compounds with biogenic Te-NPs [84].

Additionally, DLS and NTA describe the size distribution of the NPs. DLS enables the study of time-dependent oscillations and simultaneous hydrodynamic diameter and polydispersity index measurements as a result of Brownian movement. The magnetic and mechanical properties of synthesized NPs can be determined by VSM, SQUID, and DMA, respectively [78]. For investigating high-sensitivity magnetic parameters, vibrating-sample magnetometer (VSM) and superconducting quantum interference devices (SQUID) are utilized, having respective sensitivities of 10^{-6} emu and 10^{-10} emu. Tombuloglu et al. [79,81,85] have employed TEM, SEM, XRD, and VSM for analyzing the morphological, structural, and magnetic properties of NPs. The thermal characteristics of silver NPs synthesized from *Stereospermum binhchauensis* and *Jasminum subtriplinerve* were investigated by TG/DTA and the results revealed that *Stereospermum binhchauensis* Ag NPs crystallized at 315 °C and *Jasminum subtriplinerve* Ag NPs at 345 °C, respectively [86].

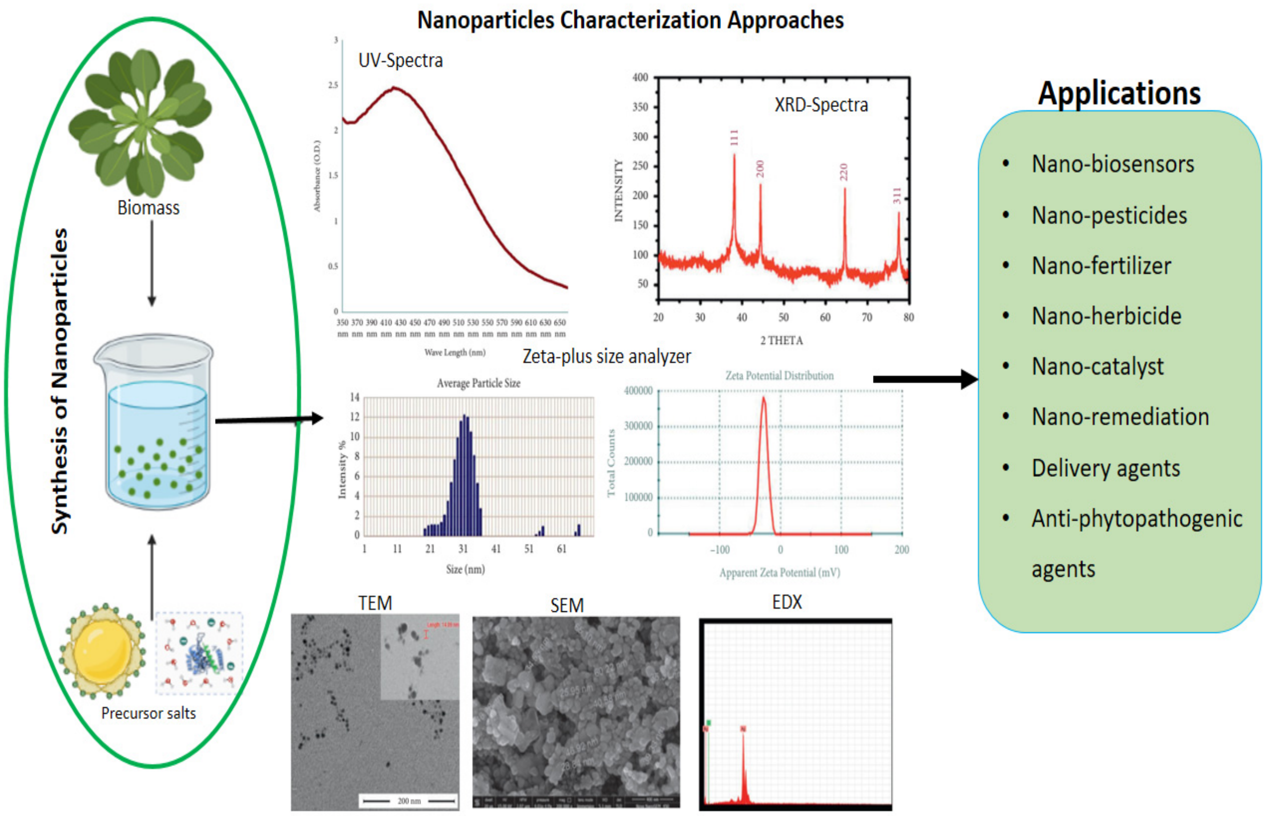

Figure 3. Methods of characterization of morphological, structural, thermal, and mechanical characteristics of biogenic nanoparticle and their application in agriculture sector [87].

4. Application of Biogenic Nanoparticles in Sustainable Agricultural Practices

The agricultural sector faces immense challenges globally that include drastic climate change, industrialization, stress factors, and environmental issues. These affect the crop productivity and plant metabolism at different levels such as carbon uptake, biochemical pathways, photosynthesis, and membrane permeability [10]. Nanotechnology has the capacity to greatly impact the agricultural sector by intelligent, target-specific delivery of nutrients and bioactive compounds, NP-mediated delivery of genetic material for crop improvement, nanofertilizers, disease management, nanosensors for detecting and pathogens and soil monitoring, nanoencapsulation of seeds, nanopesticides, nanoherbicides carbon nanotube-assisted seed germination, increased crop yield, and nutritional quality [88].

4.1. Application of Biogenic NPs as Nanofertilizers

To ensure the sustainable production of food around the world, numerous efforts are being conducted for the development of fertilizers that do not affect the environment and soil fertility in long term usage. Employment of NPs in agriculture fields in the form of nanofertilizers has increased globally to reduce the dependency on chemical fertilizers [89]. Nanofertilizers (NFs) effectively supply micronutrients and are cost-effective alternatives to conventional fertilizers by reducing phytotoxicity and environmental harm associated with chemical fertilizers [90]. Nanofertilizers assist in the precise release of nutrients that are easily absorbed by plants and produce a variety of physiochemical and morphological alterations, improved productivity, and soil fertility. Magnesium hydroxide NPs produced from *Aspergillus niger* filtrate promotes seed germination and the development of *Zea mays* plants when applied at the concentration of 500 ppm [91]. Biogenic silver NPs (25 mg/L) enhance seed germination, photosynthetic pigments, and phenolic and protein content in tomato plants [92]. Silver NPs can be utilized as an environmentally friendly nanofertilizer at a concentration of 20 ppm (safe dose for the environment and human health) [93]. Biosynthesized silver NPs significantly affected the germination of *Bacopa monnieri* seeds, improved the production of proteins and carbohydrates, and decreased the levels of phenols and antioxidant enzymes [94]. Biogenic ZnO-NPs from *Sphagneticola trilobata* improved the seed germination and fenugreek growth [95]. Sabir et al. [29] documented that zinc oxide NPs synthesized using *Bacillus subtilis* enhanced protein content, photosynthesis, and plant health of maize crop. Biogenic zinc oxide NPs from *Lemna minor* improved physiological and biochemical traits of maize plants [96]. Silver NPs improved seed germination and wheat plant growth under salinity stress conditions [97]. Foliar application of green-synthesized iron and zinc oxide NPs (500 ppm) significantly improved seed germination and yield attributes, such as total grain weight, seed length, and yield [98]. The NPs obtained from *Aloe barbadensis* increased wheat seed germination and root and shoot length and have been recognized as a source of nano-based nutrients [27]. Watermelon seed germination, growth, and yield were all improved by employing silver NPs made from agricultural leftovers [99]. Application of bio-fabricated silver NPs improved sunflower seed quality, plant production, and secondary metabolite levels in plants, as reported by Batool et al. [100]. It is thus evident that biogenic nanoparticles significantly improve plant growth parameters. However, several nanoparticles possess antimicrobial activity and alter the cell membrane structure and function, and thus cannot be used as nanofertilizers since they may impact the indigenous plant growth promoting microflora of soil. The most significant factors for the development of nano-biofertilizers consist of interaction between NPs and microbes, shelf-life, and their delivery. The use of nanoformulations can enhance the heat stability, UV inactivation, and desiccation of NFs, thus improving their shelf-life. Moreover, NPs enhance the delivery of nutrients to plants and soil and soil moisture retention capacity, owing to NP coating and microbial components.

4.2. Application of Biogenic NPs as Nanopesticides

The loss of crop productivity due to phytopathogens has a significant effect on the world economy. Pathogenic fungi, which cause more than 70% of plant diseases, are the greatest barriers of agricultural expansion [32]. NPs have been studied for agricultural applications, including germination, plant growth, stress tolerance, and disease prevention (Table 4). An innovative and highly effective method for controlling disease causing bacteria in crop plants is the usage of NPs as antimicrobials. NPs are well known for their potent nematocidal, fungicidal, and bactericidal properties due to presence of phytocompounds and biocontrol agents [101]. Subdue and Cruiser MAXX are two commercially accessible fungicides made with NPs. Some NPs damage the bacterial cell membranes, DNA replication, membrane potential, ROS metabolism, ATP production, block apoplastic trafficking, and inhibit the toxin production [102]. NPs inhibit the growth of fungal hyphae and sporangia and supress spore germination in fungi. Iron oxide NPs made from *Azidirachta indica* have an inhibitory effect on the apple plant pathogens, such as *Alternaria mali* and *Diplodia seriata* [103]. ZnO NPs control the development of *Fusarium oxysporum* in tomato plants and act as an antifungal agent [104]. Copper oxide NPs produced from actinomycetes showed antimicrobial potential against *Phythium ultimum* and *Alternaria alternate* [32]. Therefore, these biogenic NPs can be employed as nanopesticides and delivered in the form of nanoemulsions, nanocapsules or nanocages against plant pathogens. Nanopesticides are an advanced technological development and can confer an array of advantages such as better efficacy, shelf-life, low quantity of active components, decrease in pesticide usage, and minimal nutrient loss by targeted delivery of active ingredients in soil and plants. However, the effective dose of NPs must be determined by understanding the concentration dependency of the natural soil system.

Table 4. Application of biogenic nanoparticles for biotic stress management in plants.

Biogenic Nanoparticles	Host Plant	Pathogen	Response	References
Silver	Wheat	*Bipolaris sorokiniana*	Inhibit pathogens and prevent disease	[105]
Copper	Tomato	*Fusarium*	Increased plant growth and reduce disease severity	[106]
Silver	Brinjal	*Meloidogyne javanica*	Inhibit the growth of nematode	[107]
Zinc oxide	Cowpea	*Callosobruchus*	Inhibit the growth of pathogens	[82]
Neem oil-loaded zein	*Allium cepa*	*Pesticidal*	Inhibit pathogens	[108]
Copper	Potato	*Pythium ultimum*	Inhibit fungal pathogens	[32]
Silver	*Mimosa putida*	*Pseudomonas aeruginosa*, *Staphylococcus*	Inhibit the growth of pathogens	[109]
Chitosan coupled copper	Chili	*Rhizoctonia solani*, *Pythium aphanidermautum*	Inhibit the growth of pathogen and improved plant growth	[110]
Silver	Sugar beet	*Pectobacteriumcarotovorum*	Inhibit pathogens and improved sugar quality	[111]
Gold	-	*Fusarium oxysporum*, *Rhizoctoiniasolani*	Inhibit the growth of fungal pathogens	[112]

4.3. Applications of NPs in Abiotic Stress Mangament

Biogenic NPs function as potential agents for mitigating plant stress through modification in osmotic pressure, nutritional homeostasis, expression, and activity of vital antioxidative enzymes such as catalase, superoxide dismutase and peroxidase, enzymes, and proteins linked to proline and nitrogen metabolism [10], resulting in enhanced plant growth (Figure 4). Biogenic Fe-NPs synthesized from *Chaetomorpha antennina* and coated with citrate compounds reduced drought stress by improving the protective osmolyte concentration and the activity of antioxidant enzymes in *Setaria italica* [113]. Ahmed et al. [1] reported that FeO-NPs synthesized from *Bacillus* strain (RNT1) increased the nutrient uptake and upregulated the genetic mechanism, assisting in alleviating the toxic impacts of drought and cadmium in rice. Exogenous application of Zn-NPs synthesized from *Sorghum bicolor* leaf extract resulted in the induction of antioxidant defense mechanisms and improved *Abelmoschus esculentus* growth and photosynthetic rate under salinity stress [114]. Biogenic NPs regulate nutritional homeostasis in plants by providing cell protection under salt stress conditions [10]. Foliar application of plant-based Au-NPs significantly changed the amount of ion accumulation in different plant parts, increased nitrogen metabolism and enzymatic and non-enzymatic antioxidant metabolism (ascorbic acid, glutathione, glutathione peroxidase, glutathione reductase, and SOD), thus reducing the amount of ROS and lipid peroxidation [10]. Heat stress causes premature senescence, shedding, fruit damage, leaf burn, stunted growth of shoots and roots, and reduced productivity in plants. Ag-NPs synthesized from *Moringa oleifera* leaf extract on application at concentrations of 50 and 75 ppm in wheat plants caused elevation in antioxidant defense mechanisms and reduced the concentration of stress-related toxic metabolites, such as malondialdehyde and hydrogen peroxide, thus reducing the adverse impact of heat stress in wheat plants [115].

The extensive population growth and resource limitation are fundamental constraints to the sustainability of agricultural sector. Other issues are the lack of food and crops, competition for natural resources, and the need to improve crop yield under unfavorable conditions. Therefore, there is need to create new, sustainable ways that the agricultural sector can utilize to boost the effectiveness of natural resources. Biogenic NPs improve plant growth, chlorophyll content, photosynthetic rate, and antioxidant systems and thus, alleviate plant resistance to abiotic stress. However, detailed exploration of molecular and signaling mechanisms will enable a better understanding of biotic and abiotic stress-resistant crops.

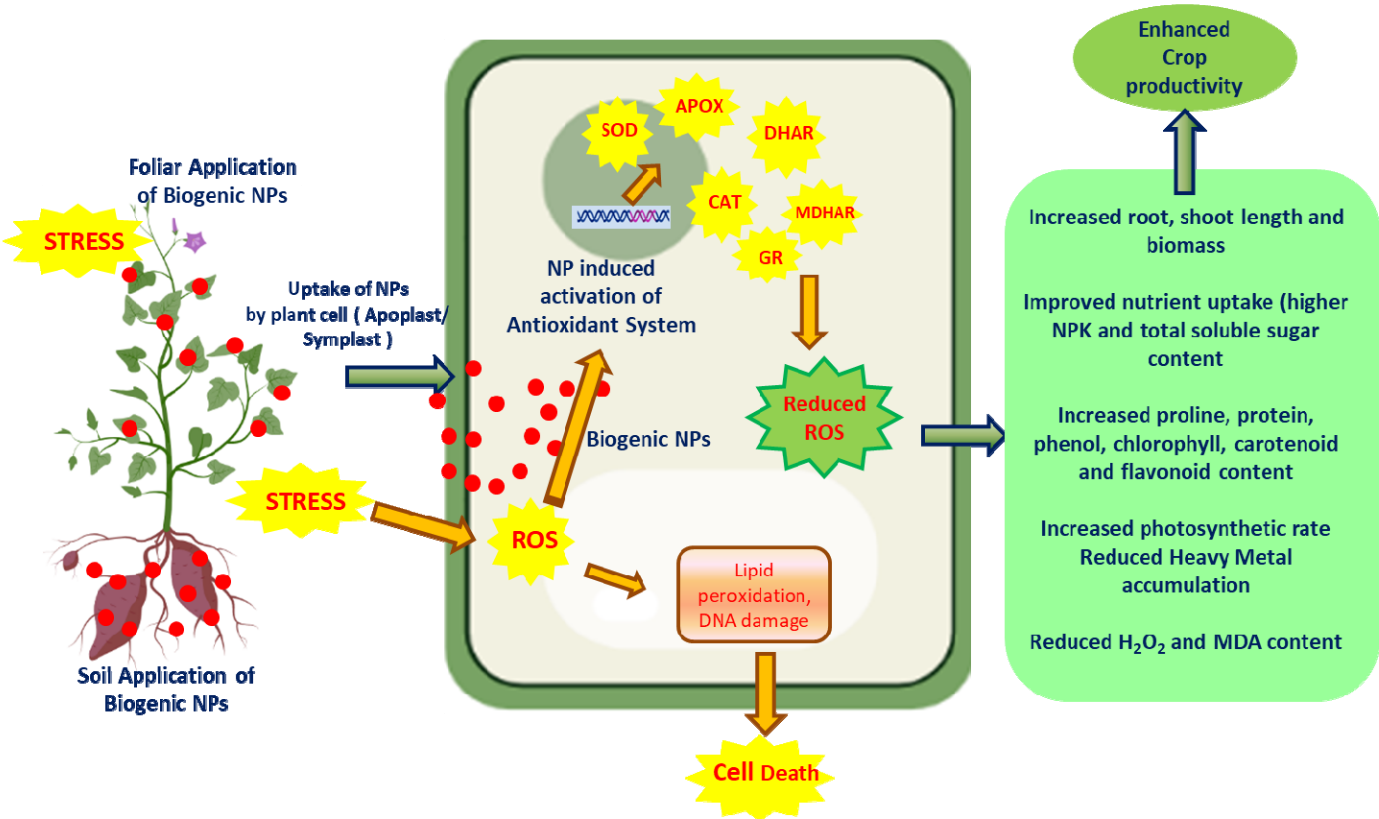

Figure 4. Application of biogenic NP for biotic and abiotic stress mitigation and enhanced crop production.

4.4. Applications of NPs as Nanobiosensors

NPs with distinctive features have also been used to modify existing technologies, including the development of "nanobiosensors", consisting of biosensors and NPs for enhanced detection capabilities. Nanobiosensors create real-time response signals that are easily collected and analyzed [116]. Different NPs including nanowires, nanotubes, and nanocomposites are used in nanobiosensors for identifying physical and chemical differences, monitoring bioactive chemicals, and quantifying contaminants. Through the use of plant extracts in the nanoengineering of eco-friendly silver NPs, Jebril et al. [117] successfully created a nanobiosensor for water quality monitoring.

Nanobiosensors can be employed in various ways along the entire agri-food supply chain, including soil condition detection, crop protection, and as diagnostic tools for pest identification during storage and quality assurance [118]. Owing to their capacity to detect processes and identify changes, nanobiosensors have contributed to the development of smart agriculture or precise farming by measuring the quantity of nutrients needed by crops, seeds viability, and shelf-life of fruits [14]. Precise farming provides complete information of field or soil conditions in order to make correct decisions to maximize yield. The rapid analysis and effective management of expensive agrochemicals, abiotic stress, and phytopathogens, all of which cause significant crop losses, are further benefits of smart plant systems. Smart nanobiosensors can accurately carry out the time-consuming task of routine plant monitoring [14]. Electrochemical detection utilizing DNA-based nanobiosensors can be used to find the *Phytophthora palmivora* with higher sensitivity that causes black pod in cocoa [119]. *Phytoplasma aurantifolia* causes witches broom disease in lemon and can be detected using nanobiosensors that employ the quantum dots fluorescence energy transfer phenomena to achieve 100% sensitivity [120]. Nanobiosensors are affixed to the plant's leaves, where waves of hydrogen peroxide (H_2O_2) signaling are seen. H_2O_2 is a chemical that reacts in plants being utilized subsequently to send signals that enable leaf cells to produce substances that protect from toxicants and predators i.e., insects [121]. Early access for the detection of plant signaling molecules in response to stress would be a good initiative in improving crop productivity and preventing agricultural losses. The use of remote sensing and hyperspectral imaging techniques help in the identification of morphological traits, unlike chlorophyll fluorescence and plant water status, which are only visible after stress accumulation [121]. Therefore, use of NP-based biosensors will help in the early detection of stress accompanying signals. Amplified temporal and spatial resolution of NP-based biosensors conjugated with remote sensing can be useful in monitoring stress signals at the initial phase, enabling its real-time in vivo detection.

Soil quality is one of the most significant aspects in agriculture, and it must be assessed for the amount of nutrients and moisture prior to any agricultural application. Soil quality can be assessed using the interaction of microbes in the rhizosphere and the biosensor [122]. Kaushal and Wani [123] developed microelectrochemical systems to detect the quality of soil and intelligent fertilizers with NPs for achieving the controlled release of fertilizers to the plant roots and sense the feedback. Nanobiosensors to analyze the moisture level and soil fertility have been developed. Ramnani et al. [124] reported that soil conditions were improved by using single-walled tubes as nanobiosensors. Single and multi-walled carbon nanotubes and graphene based nanosensors were used in detection of toxic pollutants (chlorpyrifos, pesticides, and parathion) [123]. As a futuristic approach, nano-enabled smart plants can be potential sustainable approach for the identification of early stress, which can be termed as engineered smart plant sensors. However, its efficient functioning encourages labor-intensive procedures or methods for decoding multiple chemical signals at a time with enhanced sensitivity, selectivity, and accuracy under field conditions. A proper online library needs to be set up for analyzing the change in signature molecules such as H_2O_2, N_2O, CO, and H_2S.

4.5. Application of Biogenic Nanoparticles in Bioremediation

Anthropogenic activities like industrial, agricultural, and other activities are mostly responsible for high concentrations of hazardous pollutants such as heavy metals, pesticides, textile dyes, and others [125]. NPs have been employed as adsorbents, immobilizing agents, photocatalytic agents, and filters for the removal of environmental contaminants (Figure 5). Recently, the utilization of biogenic NPs for determining, eliminating, and degrading of hazardous contaminants from different environmental matrices has increased owing to the distinct nature of NPs such as large surface area, smaller intra-particle diffusion distance, stable nature, and reusable and recyclable capacity. Additionally, these NPs can be readily synthesized and surface-functionalized, thus enhancing their applicability in remediation studies.

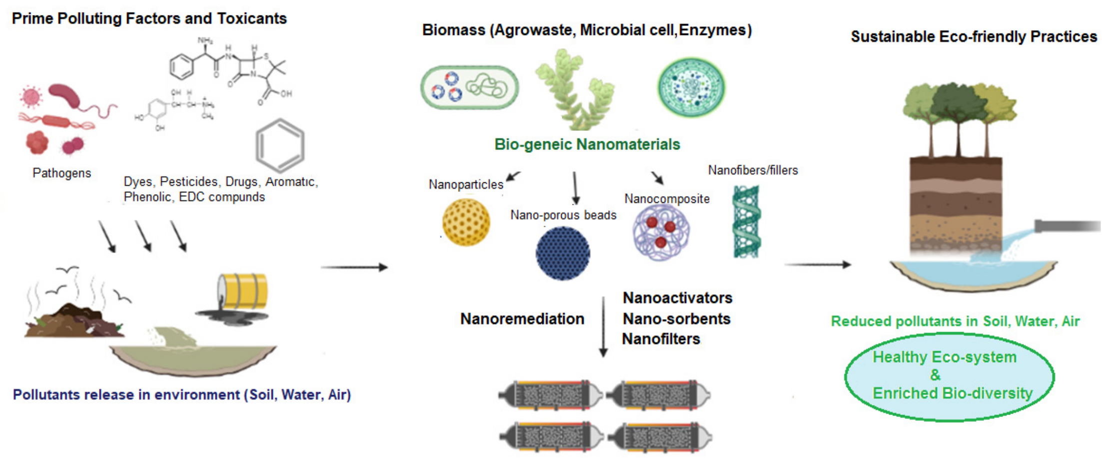

Figure 5. Role of green nanotechnology in bioremediation and environmental pollution control.

Singh et al. [126] documented that Ag and Au-NPs synthesized from *Sporosarcinakoreensis* and gold NPs functioned as a catalyst to convert 4-nitrophenol to 4-aminophenol. Gold NPs were involved in the degradation of disperse blue from textile effluent [127]. Immobilization of laccase and 2,2-binamine-di-3-ethylbenzothiazolin-6-sulfonic acid (ABTS) on the nanochitosan NPs enhanced the removal efficiency for bisphenol A, indole, and anthracene [128]. ZnO NPs made from *Justicia spicigera* degraded methylene blue to 90% after 120 min due to their photocatalytic activities [129]. Saini et al. [130] also revealed that ZnO NPs biosynthesized by *Azadirachta indica* degraded methyl orange dye (86.62%) under UV-visible light. Aromatic nitro compounds and rhodamine B were reduced by utilizing the gold NPs synthesized using *Turbinariaconoides*, as reported by Ramakrishna et al. [131]. Silver NPs made from *Sargassum myricystum* degraded 98% of methylene blue in less than an hour [132]. Silver NPs made from *Caulerpa serrulate* (algae) were efficient for congo red degradation, due to a wide surface area for the interchange of electrons [133]. Gold NPs obtained from *Scendesmusquadricauda*, *Chlorella vulgarisa*, and *Selenastrumcapricornutum* degraded polycyclic aromatic hydrocarbons [134]. CuNPs obtained from a native copper-resistant *Escherichia* sp. SINT7 functioned as a photocatalyst in the removal of azo dye [33]. Biogenic Ag NP from *Bacillus marsflavi* TEZ7 were characterized by FTIR, XRD, and TEM for the analysis of morphological and structural properties [135]. The synthesized AgNP were also employed as photocatalysts for degradation of three dyes: Direct Blue-1, Methyl Red, and Reactive Black-5, and the degradation rate was in the range of 54.14 to 96.92% [135] (Figure 6). The photocatalytic activity of biogenic Pd NPs for the degradation of textile dyes was assessed by Liang et al. [136] with a degradation rate of 81.55%, 68.45%, and 74.50% for methylene lue, methyl orange, and rhodamine B, respectively. Biogenic Ag-activated carbon NPs prepared from leaf extract of *Baccaurea motleyana* were employed as photocatalysts for the removal of the textile dye, Xenon light. The authors reported removal rates of 88.02% for methylene blue and 80.74% for rhodamine, respectively [11]. The application of biologically prepared nanosized catalysts for the degradation of environmental pollutants has emerged as a promising technique due to its remarkable efficiency, unusual antibacterial, high photocatalytic activity, and adsorbent capability and thus, have received interest for environmental cleanup and disinfection. However, the majority of reports are only of lab/bench-scale studies and their efficiency in contaminated sites is still to be evaluated in detail. Fabrication of engineered NPs with enhanced removal rates for contaminants is of prime significance for their successful applicability at the industrial scale. The shape and size of NPs are also vital for bioremediation and thus, the application of genetic engineering for controlling the particle morphology can be explored. NPs used in remediation can lead to the generation of toxic intermediary complexes, so monitoring the production and fate of these compounds at different time intervals during the treatment process and appropriate removal strategies need to be explored.

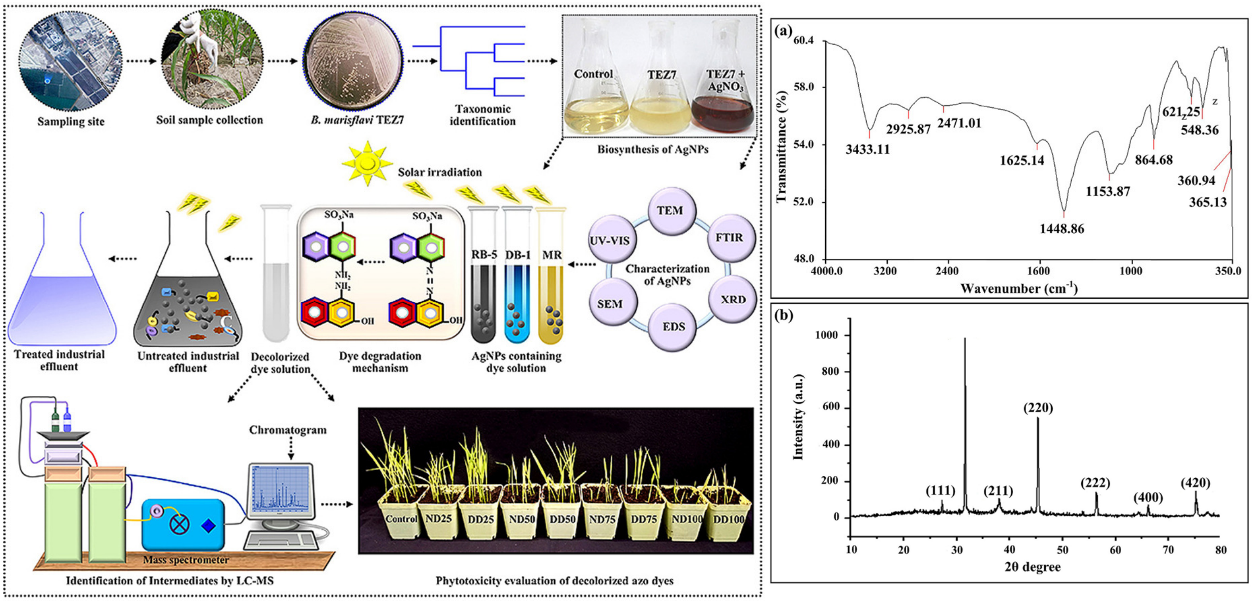

Figure 6. Biogenic synthesis of Ag_NPs using *Bacillus marisflavi* TEZ7 and its application as photocatalysts for azo dye degradation (**a**) FTIR Spectra (**b**) XRD analysis for determination of functional groups involved as capping agents [125,136].

5. Conclusions and Future Prospects

The application of different types of bio-based materials from microbes, fungi, algae, and plants in the fabrication of NPs has encouraged the development of economically viable, eco-friendly, simple, and easily scaleable approaches. As a replacement for expensive chemicals, the green approaches utilize various biomolecules (polysaccharides, proteins, and lipids) and phytochemicals to stabilize and reduce NPs and develop an environmentally friendly route. The capability to genetically modify and engineer microorganisms and plants for synthesizing NP can enable more precise control over their shape and size. Biogenic NPs are also capable of absorbing and degrading toxic contaminants. Thus, Biogenic NPs can revolutionize the agricultural and environmental sectors because of their exceptionally high biocompatible, potent, biofortifying and biocontrol ability, large surface areas, adjustable physicochemical characteristics, morphology, high regeneration capacity, and small intra-diffusion range. However, NPs synthesized by bio-based methods are monodisperse and their production rate is slow, which makes them time-consuming. Despite this, the possibility of using these processes for large-scale synthesis may arise if microbes are screened and growth parameters (temperature, pH, agitation, raw material concentration) are optimized. The bioremediation potential of green NPs has been exclusively demonstrated, but their commercial application is limited because of factors such as large-scale synthesis, long-term stability, and less exploration.

Alternative methods are currently being employed to address these setbacks, such as immobilizing microbes on nanomatrixes and coupling nanotechnology with other green technologies, such as aerobic digesters, membrane bioreactors, biosensors, microbial fuel cells, and electrospun nanofiber webs. Addionally, the biogenic NPs treat contaminants in such a manner that leftover residues are biocompatible and easily removed by filtration or precipitation processes. Various valuable by-products including construction materials may be fabricated by using residual contaminants by the incorporation of biochar in a circular bioeconomy concept. Aside from the fact that NPs manufactured using green methods are less toxic than those fabricated conventionally, limited studies on their toxicity for humans and the environment are available. The impact of biogenic NPs on different ecosystems must be assessed for their application to agriculture and the environment. A scale-up study in algal and plant-mediated NP synthesis has yet to be done, and there are still challenges associated with slow biosynthesis rates as well as controlling NP size, dispersity, and morphology. Immense efforts are also required for a better understanding of NP synthesis and plant signaling processes after NP application, transforming these laboratory products into commercial form by the successful large-scale industrial setups for various applications be necessary for future research.

In addition, nanotechnology can be combined with advanced technologies like artificial intelligence (AI), bioinformatics, cloud computing, internet of things (IoTs), machine learning, and 5G communication to replace the conventional time- and resource-intensive strategies. Advanced communication networks and IoTs can also be used for real-time detection and monitoring of emerging pollutants and plant stress parameters by using nanorobotic sensing devices. In addition to monitoring the individual pollutants and stress factors, NM may also assist in the development of a point-of-solution module. Moreover, AI may be used to investigate various microorganisms or bio-reductants for NP fabrication in silico. Hence, in order to fulfil the world's food demand and the aims of sustainable development, these combined tactics have the potential to revolutionize present agricultural practices and bioremediation strategies.

Author Contributions: Conceptualization, G.B. and A.D.; methodology, G.B. and A.D.; software, S.G. (Sanjay Gupta) and A.G.; validation, S.M. and S.R.; formal analysis, P.S., S.S.S.; data curation, V.D.R., P.C., S.G. (Sanjay Gupta) and S.M.; writing—original draft preparation, G.B., A.D., S.M. and S.G. (Saurabh Gangola); writing—review and editing, S.M., G.B. and P.S.; visualization, V.D.R., S.S.S. and T.M.; supervision, S.M. and P.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Authors acknowledge the support provided by their respective institutions.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ahmed, T.; Noman, M.; Manzoor, N.; Shahid, M.; Abdullah, M.; Ali, L.; Wang, G.; Hashem, A.; Al-Arjani, A.F.; Alqarawi, A.A.; et al. Nanoparticle-based amelioration of drought stress and cadmium toxicity in rice via triggering the stress responsive genetic mechanisms and nutrient acquisition. *Ecotoxicol. Environ. Saf.* **2021**, *209*, 111829. [CrossRef] [PubMed]
2. Khan, M.I.R.; Palakolanu, S.R.; Chopra, P.; Rajurkarm, A.B.; Gupta, R.; Iqbal, N.; Maheshwari, C. Improving drought tolerance in rice: Ensuring food security through multi- dimensional approaches. *Physiol. Plant.* **2021**, *172*, 645–668. [CrossRef] [PubMed]
3. Chaudhary, P.; Chaudhary, A.; Bhatt, P.; Kumar, G.; Khatoon, H.; Rani, A.; Kumar, S.; Sharma, A. Assessment of Soil Health Indicators Under the Influence of Nanocompounds and Bacillus spp. in Field Condition. *Front. Environ. Sci.* **2022**, *9*, 769871. [CrossRef]
4. Nejatzadeh, F. Effect of silver nanoparticles on salt tolerance of *Satureja hortensis* L. during in vitro and in vivo germination tests. *Heliyon* **2021**, *7*, e05981. [CrossRef] [PubMed]
5. Abdelkhalek, A.; El-Gendi, H.; Alotibi, F.O.; Al-Askar, A.A.; Elbeaino, T.; Behiry, S.I.; Abd-Elsalam, K.A.; Moawad, H. *Ocimum basilicum*-mediated synthesis of silver nanoparticles induces innate immune responses against cucumber mosaic virus in squash. *Plants* **2022**, *11*, 2707. [CrossRef]
6. Patil, S.; Chandrasekaran, R. Biogenic nanoparticles: A comprehensive perspective in synthesis, characterization, application and its challenges. *J. Genet. Eng. Biotechnol.* **2020**, *18*, 67. [CrossRef]
7. Mughal, B.; Zaidi, S.Z.J.; Zhang, X.; Hassan, S.U. Biogenic Nanoparticles Synthesis, Characterisation and Applications. *Appl. Sci.* **2021**, *11*, 2598. [CrossRef]

8. Sengani, M.; Chakraborty, S.; Balaji, M.P.; Govindasamy, R.; Alahmadi, T.A.; Obaid, S.A.; Karuppusamy, I.; Chi, N.T.L.; Brindhadevi, K.; Devi, R.V. Anti-diabetic efficacy and selective inhibition of methyl glyoxal, intervention with biogenic Zinc oxide nanoparticle. *Environ. Res.* **2023**, *216*, 114475. [CrossRef]
9. Jaiswal, K.K.; Banerjee, I.; Dutta, S.; Verma, R.; Gunti, L.; Awasthi, S.; Bhushan, M.; Kumar, V.; Alajmi, M.F.; Hussain, A. Microwave-assisted polycrystalline Ag/AgO/AgCl nanocomposites synthesis using banana corm (rhizome of *Musa* sp.) extract: Characterization and antimicrobial studies. *J. Ind. Eng. Chem.* **2022**, *107*, 145–154. [CrossRef]
10. Chakraborty, S.; Singh, A.; Roychoudhury, A. Biogenic nanoparticles and generation of abiotic stress-resilient plants: A new approach for sustainable agriculture. *Plant Stress* **2022**, *6*, 100117. [CrossRef]
11. Kavitha, G.; Kumar, J.V.; Pavithra, S.; Komal, M.; Nivetha, M.S.; Kayalvizhi, R.; Abirami, N. Biogenic synthesis of argentum nanocomposites for visible light photocatalyst of dye degradation. *Chem. Phys. Lett.* **2022**, *809*, 140159. [CrossRef]
12. Heinemann, M.G.; Rosa, C.H.; Rosa, G.R.; Dias, D. Biogenic synthesis of gold and silver nanoparticles used in environmental applications: A review. *Trends Environ. Anal. Chem.* **2021**, *30*, e00129. [CrossRef]
13. Saha, P.; Kim, B.S. Plant extract and agricultural waste-mediated synthesis of silver nanoparticles and their biochemical activities. *Green Synth. Silver Nanomat.* **2022**, 285–315. [CrossRef]
14. Mittal, D.; Kumar, A.; Balasubramaniam, B.; Thakur, R.; Siwal, S.S.; Saini, R.V.; Gupta, R.K.; Saini, A.K. Synthesis of Biogenic silver nanoparticles using plant growth promoting bacteria: Potential use as biocontrol agent against phytopathogens. *Biomat. Polym. Horiz.* **2022**, *1*, 22–31. [CrossRef]
15. Rai, M.; Ingle, A.P.; Trzcinska-Wencel, J.; Wypij, M.; Bonde, S.; Yadav, A.; Kratošová, G.; Golinska, P. Biogenic Silver Nanoparticles: What We Know and What Do We Need to Know? *Nanomaterials* **2021**, *11*, 2901. [CrossRef]
16. Revati, K.; Pandey, B.D. Microbial synthesis of iron-based nanomaterials—A review. *Bull. Mater. Sci.* **2011**, *34*, 191–198.
17. Durán, N.; Marcato, P.D.; Durán, M.; Yadav, A.; Gade, A.; Rai, M. Mechanistic aspects in the biogenic synthesis of extracellular metal nanoparticles by peptides, bacteria, fungi, and plants. *Appl. Microbiol. Biotechnol.* **2011**, *90*, 1609–1624. [CrossRef]
18. Wadhwani, S.A.; Shedbalkar, U.U.; Singh, R.; Chopade, B.A. Biogenic selenium nanoparticles: Current status and future prospects. *Appl. Microbiol. Biotechnol.* **2016**, *100*, 2555–2566. [CrossRef]
19. Nangia, Y.; Wangoo, N.; Goyal, N.; Sharma, S.; Wu, J.S.; Dravid, V.; Shekhawat, G.S.; Suri, C.R. Facile biosynthesis of phosphate capped gold nanoparticles by a bacterial isolate *Stenotrophomonas maltophilia*. *Appl. Phys. Lett.* **2009**, *94*, 233901. [CrossRef]
20. Allam, N.G.; Ismail, G.A.; El-Gemizy, W.M.; Salem, M.A. Biosynthesis of silver nanoparticles by cell-free extracts from some bacteria species for dye removal from wastewater. *Biotechnol. Lett.* **2019**, *41*, 379–389. [CrossRef]
21. Gahlawat, G.; Choudhary, A.R. A review on the biosynthesis of metal and metal salt nanoparticles by microbes. *RSC Adv.* **2019**, *9*, 12944–12967. [CrossRef] [PubMed]
22. Graves, J.L.; Tajkarimi, M.; Cunningham, Q.; Campbell, A.; Nonga, H.; Harrison, S.H. Rapid evolution of silver nanoparticles resistance in Escherichia colli. *Front. Genet.* **2015**, *6*, 42. [CrossRef] [PubMed]
23. Shi, L.; Rosso, K.M.; Clarke, T.A.; Richardson, D.J.; Zachara, J.M.; Fredrickson, J.K. Molecular underpinnings of Fe (III) oxide reduction by Shewanella Oneidensis MR-1. *Front. Microbiol.* **2012**, *3*, 50. [CrossRef] [PubMed]
24. Eramabadi, P.; Masoudi, M.; Makhdoumi, A.; Mashreghi, M. Microbial cell lysate supernatant (CLS) alteration impact on platinum nanoparticles fabrication, characterization, antioxidant and antibacterial activity. *Mat. Sci. Eng. C* **2020**, *117*, 111292. [CrossRef]
25. Elbeshehy, E.K.F.; Elazzazy, A.M.; Aggelis, G. Silver nanoparticles synthesis mediated by new isolates of *Bacillus* spp., nanoparticle characterization and their activity against Bean Yellow Mosaic Virus and human pathogens. *Front. Microbiol.* **2015**, *6*, 453. [CrossRef]
26. Mathivanan, K.; Selva, R.; Chandirika, J.U.; Govindarajan, R.K.; Srinivasan, R.; Annadurai, G.; Duc, P.A. Biologically synthesized silver nanoparticles against pathogenic bacteria: Synthesis, calcination and characterization. *Biocatal. Agric. Biotechnol.* **2019**, *22*, 101373. [CrossRef]
27. Singh, J.; Kumar, S.; Alok, A.; Upadhyay, S.K.; Rawat, M.; Tsang, D.C.W. The Potential of Green Synthesized Zinc Oxide Nanoparticles as Nutrient Source for Plant Growth. *J. Clean. Prod.* **2019**, *214*, 1061–1070. [CrossRef]
28. Dhandapani, P.; Prakash, A.A.; AlSalhi, M.S.; Maruthamuthu, S.; Devanesan, S.; Rajasekar, A. Ureolytic bacteria mediated synthesis of hairy ZnO nanostructure as photocatalyst for decolorization of dyes. *Mater. Chem. Phys.* **2020**, *243*, 122619. [CrossRef]
29. Sabir, S.; Zahoor, M.A.; Waseem, M.; Siddique, M.H.; Shafique, M.; Imran, M.; Hayat, S.; Malik, I.R.; Muzammil, S. Biosynthesis of ZnO Nanoparticles using *Bacillus subtilis*: Characterization and nutritive significance for promoting plant growth in *Zea mays* L. *Dose Res.* **2020**, *18*, 1559325820958911. [CrossRef]
30. Bharathi, S.; Kumaran, S.; Suresh, G.; Ramesh, M.; Thangamani, V.; Pughazhventhan, S.R. Extracellular synthesis of nanoselenium from fresh water bacteria Bacillus sp., and its validation of antibacterial and cytotoxic potential. *Biocatal. Agric. Biotechnol.* **2020**, *27*, 101655. [CrossRef]
31. Tugarova, A.V.; Mamchenkova, P.V.; Khanadeev, V.A.; Kamnev, A.K. Selenite reduction by the rhizobacterium *Azospirillum brasilense*, synthesis of extracellular selenium nanoparticles and their characterisation. *New Biotechnol.* **2020**, *58*, 17–24. [CrossRef]
32. Hassan, S.E.; Fouda, A.; Radwan, A.A.; Salem, S.S.; Barghoth, M.G.; Awad, M.A.; Abdo, A.M.; El-Gamal, M.S. Endophytic actinomycetes *Streptomyces* spp. mediated biosynthesis of copper oxide nanoparticles as a promising tool for biotechnological applications. *J. Biol. Inorg. Chem.* **2019**, *24*, 377–393. [CrossRef]

33. Noman, M.; Shahid, M.; Ahmed, T.; Niazi, M.B.K.; Hussain, S.; Song, F. Use of biogenic copper nanoparticles synthesized from a native *Escherichia* sp. as photocatalysts for azo dye degradation and treatment of textile effluents. *Environ. Pollut.* **2020**, *257*, 113514. [CrossRef]
34. Mukherjee, P.; Roy, M.; Mandal, B.P.; Dey, G.K.; Mukherjee, P.K.; Ghatak, J.; Tyagi, A.K.; Kale, S.P. Green synthesis of highly stabilized nanocrystalline silver particles by a nonpathogenic and agriculturally important fungus *T. asperellum*. *Nanotechnology* **2008**, *19*, 103–110.
35. Jalal, M.; Ansari, M.A.; Alzohairy, M.A.; Ali, S.G.; Khan, H.M.; Almatroudi, A.; Raees, K. Biosynthesis of silver nanoparticles from oropharyngeal *Candida glabrata* Isolates and their antimicrobial activity against clinical strains of bacteria and fungi. *Nanomaterials* **2018**, *8*, 586. [CrossRef]
36. Kalpana, V.N.; Kataru, B.A.S.; Sravani, N.; Vigneshwari, T.; Panneerselvam, A.; Rajeswari, V.D. Biosynthesis of zinc oxide nanoparticles using ulture filtrates of *Aspergillus niger*: Antimicrobial textiles and dye degradation studies. *Open Nanomat.* **2018**, *3*, 48–55.
37. Krishna, G.; Srileka, V.; Charya, M.A.S.; Serea, E.S.A.; Shalan, A.E. Biogenic synthesis and cytotoxic effects of silver nanoparticles mediated by white rot fungi. *Heliyon* **2021**, *7*, e06470. [CrossRef]
38. Vijayanandan, A.S.; Balakrishnan, R.M. Biosynthesis of cobalt oxide nanoparticles using endophytic fungus *Aspergillus nidulans*. *J. Environ. Manag.* **2018**, *218*, 442–450. [CrossRef]
39. Mukherjee, P.; Ahmad, A.; Mandal, D.; Senapati, S.; Sainkar, S.R.; Khan, M.I.; Ramani, R.; Parischa, R.; Ajayakumar, P.V.; Alam, M. Bioreduction of $AuCl^{4-}$ ions by the fungus, *Verticillium* sp. and surface trapping of the gold nanoparticles formed. *Angew. Chem. Int. Ed.* **2001**, *40*, 3585–3588. [CrossRef]
40. Spagnoletti, F.N.; Spedalieri, C.; Kronberg, F.; Giacometti, R. Extracellular biosynthesis of bactericidal Ag/AgCl nanoparticles for crop protection using the fungus *Macrophomina phaseolina*. *J. Environ. Manag.* **2019**, *231*, 457–466. [CrossRef]
41. Win, T.T.; Khan, S.; Fu, P. Fungus-(*Alternaria* sp.) mediated silver nanoparticles synthesis, characterization, and screening of antifungal activity against some phytopathogens. *J. Nanotechnol.* **2020**, *29*, 8828878. [CrossRef]
42. Tesser, M.E.; Guilger, M.; Bilesky-José, N.; Risso, W.E.; de Lima, R.; dos Reis Martinez, C.B. Biogenic metallic nanoparticles (Ag, TiO2, Fe) as potential fungicides for agriculture: Are they safe for the freshwater mussel *Anodontites trapesialis*? *Chemosphere* **2022**, *309*, 136664. [CrossRef] [PubMed]
43. Muñoz, A.J.; Espínola, F.; Ruiz, E.; Cuartero, M.; Castro, E. Biotechnological use of the ubiquitous fungus *Penicillium* sp. 8L2, Biosorption of Ag (I) and synthesis of silver nanoparticles. *J. Environ. Manag.* **2022**, *316*, 115281. [CrossRef]
44. Das, P.; Barua, S.; Sarkar, S.; Chatterjee, S.K.; Mukherjee, S.; Goswami, L.; Das, S.; Bhattacharya, S.; Karak, N.; Bhattacharya, S.S. Mechanism of toxicity and transformation of silver nanoparticles: Inclusive assessment in earthworm-microbe-soil-plant system. *Geoderma* **2018**, *314*, 73–84. [CrossRef]
45. Mahanty, S.; Bakshi, M.; Ghosh, S.; Chatterjee, S.; Bhattacharyya, S.; Das, P.; Das, S.; Chaudhuri, P. Green synthesis of iron oxide nanoparticles mediated by filamentous fungi isolated from Sundarban mangrove ecosystem, India. *BioNanoScience* **2019**, *9*, 637–651. [CrossRef]
46. Grandmontagne, D.; Navarro, D.; Neugnot-Roux, V.; Ladevèze, S.; Berrin, J.G. The Secretomes of *Aspergillus japonicus* and *Aspergillus terreus* Supplement the Rovabio® Enzyme Cocktail for the Degradation of Soybean Meal for Animal. *Feed. J. Fungi* **2021**, *7*, 278. [CrossRef]
47. Sharma, B.; Purkayastha, D.D.; Hazra, S.; Gogoi, L.; Bhattacharjee, C.R.; Ghosh, N.N.; Rout, J. Biosynthesis of gold nanoparticles using a freshwater green alga, *Prasiolacrispa*. *Mat. Lett.* **2014**, *116*, 94–97. [CrossRef]
48. Senapati, S.; Syed, A.; Moeez, S.; Kumar, A.; Ahmad, A. Intracellular synthesis of gold nanoparticles using alga *Tetraselmis kochinensis*. *Mat. Lett.* **2012**, *79*, 116–118. [CrossRef]
49. Jena, J.; Pradhan, N.; Aishvarya, V.; Nayak, R.R.; Dash, B.P.; Sukla, L.B.; Panda, P.K.; Mishra, B.K. Biological sequestration and retention of cadmium as CdS nanoparticles by the microalga *Scenedesmus-24*. *J. Appl. Phycol.* **2012**, *27*, 2251–2260. [CrossRef]
50. Subramaniyam, V.; Ramraj, S.; Bose, S.; Thavamani, P.; Megharaj, M.; Chen, Z.; Naidu, R. Chlorococcum sp. MM11- a novel Phyco-nanofactoryfor the synthesis of iron NP. *J. Appl. Phycol.* **2015**, *27*, 1861–1869. [CrossRef]
51. Rao, M.D.; Pennathur, G. Green synthesis and characterization of cadmium sulphide nanoparticles from *Chlamydomonas reinhardtii* and their application as photocatalysts. *Mat. Res. Bull.* **2017**, *85*, 64–73. [CrossRef]
52. Sayadi, M.H.; Salmani, N.; Heidari, A.; Rezaei, M.R. Bio-synthesis of palladium nanoparticle using *Spirulina platensis* alga extract and its application as adsorbent. *Surf. Inter.* **2018**, *10*, 136–143. [CrossRef]
53. Massironi, A.; Morelli, A.; Grassi, L.; Puppi, D.; Braccini, S.; Maisetta, G.; Chiellini, F. Ulvan as novel reducing and stabilizing agent from renewable algal biomass: Application to green synthesis of silver nanoparticles. *Carbohydr. Polym.* **2019**, *203*, 310–321. [CrossRef]
54. Itroutwar, P.D.; Kasivelu, G.; Raguraman, V.; Malaichamy, K.; Sevathapandian, S.K. Effects of biogenic zinc oxide nanoparticles on seed germination and seedling vigor of maize (*Zea mays*). *Biocatal. Agricul. Biotechnol.* **2020**, *29*, 101778. [CrossRef]
55. Öztürk, B.Y.; Gürsu, B.Y.; Dag, I. Antibiofilm and antimicrobial activities of green synthesized silver nanoparticles using marine red algae *Gelidium corneum*. *Process Biochem.* **2020**, *89*, 208–219. [CrossRef]
56. Abdel-Raouf, N.; Al-Enazi, N.M.; Ibraheem, I.B.M.; Alharbi, R.M.; Alkhulaifi, M.M. Biosynthesis of silver nanoparticles by using of the marine brown alga *Padina pavonia* and their characterization. *Saudi J. Biol. Sci.* **2019**, *26*, 1207–1215. [CrossRef]

57. Annamalai, J.; Nallamuthu, T. Green synthesis of silver nanoparticles: Characterization and determination of antibacterial potency. *Appl. Nanosci.* **2016**, *6*, 259–265. [CrossRef]
58. Choudhary, M.K.; Kataria, J.; Sharma, S. Evaluation of the kinetic and catalytic properties of biogenically synthesized silver nanoparticles. *J. Clean. Prod.* **2018**, *198*, 882–890. [CrossRef]
59. Ahmad, N.; Sharma, S.; Alam, M.K.; Singh, V.N.; Shamsi, S.F.; Mehta, B.R. Rapid synthesis of silver nanoparticles using dried medicinal plant of basil. *Colloids Surf. B* **2010**, *81*, 81–86. [CrossRef]
60. Kumar, P.V.; Kala, S.M.J.; Prakash, K.S. Green synthesis of gold nanoparticles using croton *Caudatus geisel* leaf extract and their biological studies. *Mater. Lett.* **2019**, *236*, 19–22. [CrossRef]
61. Kumar, B.; Smita, K.; Cumbal, L.; Debut, A. Synthesis of silver nanoparticles using Sacha inchi (*Plukenetia volubilis* L.) leaf extracts. *Saudi J. Biol. Sci.* **2014**, *21*, 605–609. [CrossRef] [PubMed]
62. Gavade, N.L.; Kadam, A.N.; Suwarnkar, M.B.; Ghodake, V.P.; Garadkar, K.M. Biogenic synthesis of multi-applicative silver nanoparticles by using *Ziziphus Jujuba* leaf extract. *Spectrochim. Acta A Mol. Biomol. Spectrosc.* **2015**, *136*, 953–960. [CrossRef] [PubMed]
63. Joseph, S.; Mathew, B. Microwave-assisted green synthesis of silver nanoparticles and the study on catalytic activity in the degradation of dyes. *J. Mol. Liq.* **2015**, *204*, 184–191. [CrossRef]
64. Periyasami, G.; Palaniappan, S.; Karuppiah, P.; Rahaman, M.; Karthikeyan, P.; Aldalbahi, A.; Al-Dhabi, N.A. Biogenic Silver Nanoparticles Fabricated by *Euphorbia granulate* Forssk's Extract: Investigating the Antimicrobial, Radical Scavenging, and Catalytic Activities. *J. Nanomat.* **2022**, *10*, 3864758. [CrossRef]
65. Sharma, T.S.; Selvakumar, K.; Hwa, K.Y.; Sami, P.; Kumaresan, M. Biogenic fabrication of gold nanoparticles using *Camellia japonica* L. leaf extract and its biological evaluation. *J. Mat. Res. Technol.* **2019**, *8*, 1412–1418. [CrossRef]
66. Guo, M.; Li, W.; Yang, F.; Liu, H. Controllable biosynthesis of gold nanoparticles from a *Eucommia ulmoides* bark aqueous extract. *Spectrochim. Acta A Mol. Biomol. Spectrosc.* **2015**, *142*, 73–79. [CrossRef]
67. Nasrollahzadeh, M.; Sajadi, S.M.; Vartooni, A.R.; Bagherzadeh, M. Green synthesis of Pd/CuO nanoparticles by *Theobroma cacao* L. seeds extract and their catalytic performance for the reduction of 4- nitrophenol and phosphine-free Heck coupling reaction under aerobic conditions. *J. Colloid Interface Sci.* **2015**, *448*, 106–113. [CrossRef]
68. Darroudi, M.; Sarani, M.; Oskuee, R.K.; Zak, A.K.; Hosseini, H.A.; Gholami, L. Green synthesis and evaluation of metabolic activity of starch mediated nanoceria. *Ceram. Int.* **2014**, *40*, 2041–2045. [CrossRef]
69. Kumar, B.; Smita, K.; Debut, A.; Cumbal, L. Andean Sacha Inchi (*Plukenetia volubilis* L.) leaf-mediated synthesis of Cu_2O nanoparticles: A low-cost approach. *Bioengineering* **2020**, *7*, 54. [CrossRef]
70. Prasad, K.S.; Gandhi, P.; Selvaraj, K. Synthesis of green nano iron particles (GnIP) and their application in adsorptive removal of As (III) and As (V) from aqueous solution. *Appl. Surface. Sci.* **2014**, *317*, 1052–1059. [CrossRef]
71. Wang, T.; Jin, X.; Chen, Z.; Megharaj, M.; Naidu, R. Green synthesis of Fe nanoparticles using eucalyptus leaf extracts for treatment of eutrophic wastewater. *Sci. Total Environ.* **2014**, *466–467*, 210–213. [CrossRef]
72. Venkateswarlu, S.; Kumar, B.N.; Prasad, C.H.; Venkateswarlu, P.; Jyothi, N.V.V. Bio-inspired green synthesis of Fe_3O_4 spherical magnetic nanoparticles using *Syzygiumcumini* seed extract. *Phys. B* **2014**, *449*, 67–71. [CrossRef]
73. Qu, J.; Yuan, X.; Wang, X.; Shao, P. Zinc accumulation and synthesis of ZnO nanoparticles using *Physalis alkekengi*. *Environ. Pollut.* **2011**, *159*, 1783–1788. [CrossRef]
74. Suresh, A.K. Extracellular bio-production and characterization of small monodispersed CdSe quantum dot nanocrystallites. *Spectrochim. Acta Part A Mol. Biomol. Spectrosc.* **2014**, *130*, 344–349. [CrossRef]
75. Abdelkhalek, A.; Al-Askar, A.A. Green synthesized ZnO nanoparticles mediated by *Mentha spicata* extract induce plant systemic resistance against Tobacco mosaic virus. *Appl. Sci.* **2020**, *10*, 5054. [CrossRef]
76. Srivastava, V.; Sharma, Y.C.; Sillanpää, M. Green synthesis of magnesium oxide nanoflower and its application for the removal of divalent metallic species from synthetic waste water. *Ceram. Int.* **2015**, *41*, 6702–6709. [CrossRef]
77. Abdelkhalek, A.; Qari, S.H.; Abu-Saied, M.A.; Khalil, A.M.; Younes, H.A.; Nehela, Y.; Behiry, S.I. Chitosan nanoparticles inactivate alfalfa mosaic virus replication and boost innate immunity in *Nicotiana glutinosa* plants. *Plants* **2021**, *10*, 2701. [CrossRef]
78. Joudeh, N.; Linke, D. Nanoparticle classification, physicochemical properties, characterization, and applications: A comprehensive review for biologists. *J. Nanobiotechnol.* **2022**, *20*, 262. [CrossRef]
79. Tombuloglu, H.; Slimani, Y.; Tombuloglu, G.; Alshammari, T.; Almessiere, M.; Korkmaz, A.D.; Baykal, A.; Samia, A.C.S. Engineered magnetic nanoparticles enhance chlorophyll content and growth of barley through the induction of photosystem genes. *Environ. Sci. Pollut. Res.* **2020**, *27*, 3431–3432. [CrossRef]
80. Raj, S.; Trivedi, R.; Soni, V. Biogenic Synthesis of Silver Nanoparticles, Characterization and Their Applications—A Review. *Surfaces* **2022**, *5*, 67–90. [CrossRef]
81. Tombuloglu, H.; Slimani, Y.; Alshammari, T.; Tombuloglu, G.; Almessiere, M.; Baykal, A.; Ercan, I.; Ozcelik, S.; Demirci, T. Magnetic Behavior and Nutrient Content Analyses of Barley (*Hordeum vulgare* L.) Tissues upon $CoNd_{0.2}Fe_{1.8}O_4$ Magnetic Nanoparticle Treatment. *J. Soil Sci. Plant Nutr.* **2020**, *20*, 357–366. [CrossRef]
82. Balasubramanian, S.; Kala, S.M.J.; Pushparaj, T.L. Biogenic synthesis of gold nanoparticles using *Jasminum auriculatum* leaf extract and their catalytic, antimicrobial and anticancer activities. *J. Drug Deliv. Sci. Technol.* **2020**, *57*, 101620. [CrossRef]
83. Khan, I.; Saeed, K.; Khan, I. Nanoparticles: Properties, applications and toxicities. *Arab. J. Chem.* **2019**, *12*, 908–931. [CrossRef]

84. Nwoko, K.C.; Liang, X.; Perez, M.A.; Krupp, E.; Gadd, G.M.; Feldmann, J. Characterisation of selenium and tellurium nanoparticles produced by *Aureobasidium pullulans* using a multi-method approach. *J. Chromatogr. A* **2021**, *1642*, 462022. [CrossRef] [PubMed]
85. Tombuloglu, H.; Anıl, I.; Akhtar, S.; Turumtay, H.; Sabit, H.; Slimani, Y.; Almessiere, M.; Baykal, A. Iron oxide nanoparticles translocate in pumpkin and alter the phloem sap metabolites related to oil metabolism. *Sci. Hortic.* **2020**, *265*, 109223. [CrossRef]
86. Nguyen, T.M.T.; Huynh, T.T.T.; Dang, C.H.; Mai, D.T.; Nguyen, T.T.N.; Nguyen, D.T. Novel biogenic silver nanoparticles used for antibacterial effect and catalytic degradation of contaminants. *Res. Chem. Intermed.* **2020**, *46*, 1975–2090. [CrossRef]
87. Purohit, A.; Sharma, R.; Ramakrishnan, R.S.; Sharma, S.; Kumar, A.; Jain, D. Biogenic synthesis of Silver Nanoparticles (AgNPs) Using Aqueous Leaf Extract of *Buchanania lanzan* Spreng and Evaluation of Their Antifungal Activity against Phytopathogenic Fungi. *Bioinorg. Chem. Appl.* **2022**, *2022*, 6825150. [CrossRef]
88. Liu, R.; Lal, R. Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. *Sci. Total Environ.* **2015**, *514*, 131–139. [CrossRef]
89. Agri, U.; Chaudhary, P.; Sharma, A.; Kukreti, B. Physiological response of maize plants and its rhizospheric microbiome under the influence of potential bioinoculants and nanochitosan. *Plant Soil.* **2022**, *474*, 451–468. [CrossRef]
90. Avila-Quezada, G.D.; Ingle, A.P.; Golińska, P.; Rai, M. Strategic applications of nano-fertilizers for sustainable agriculture: Benefits and bottlenecks. *Nanotechnol. Rev.* **2022**, *11*, 2123–2140. [CrossRef]
91. Shinde, S.; Paralikar, P.; Ingle, A.P.; Rai, M. Promotion of seed germination and seedling growth of *Zea mays* by magnesium hydroxide nanoparticles synthesized by the filtrate from *Aspergillus niger*. *Arab. J. Chem.* **2020**, *13*, 3172–3182. [CrossRef]
92. Salih, A.M.; Qahtan, A.A.; Al-Qurainy, F.; Al-Munqedhi, B.M. Impact of Biogenic Ag-Containing Nanoparticles on Germination Rate, Growth, Physiological, Biochemical Parameters, and Antioxidants System of Tomato (*Solanum tuberosum* L.) In Vitro. *Processes* **2022**, *10*, 825. [CrossRef]
93. Fouda, M.M.; Abdelsalam, N.R.; El-Naggar, M.E.; Zaitoun, A.F.; Salim, B.M.; Bin-Jumah, M.; Allam, A.; Abo-Marzoka, S.A.; Kandil, E.E. Impact of high throughput green synthesized silver nanoparticles on agronomic traits of onion. *Int. J. Biol. Macromol.* **2020**, *149*, 1304–1317. [CrossRef]
94. Krishnaraj, C.; Jagan, E.G.; Ramachandran, R.; Abirami, S.M.; Mohan, N.; Kalaichelvan, P.T. Effect of biologically synthesized silver nanoparticles on *Bacopa monnieri* (Linn.) Wettst. plant growth metabolism. *Proc. Biochem.* **2012**, *47*, 51–658. [CrossRef]
95. Shaik, A.M.; David, R.M.; Reddy, D.R.S. Green synthesis of zinc oxide nanoparticles using aqueous root extract of *Sphagneticola trilobata* Lin and investigate its role in toxic metal removal, sowing germination and fostering of plant growth. *Inorg. Nano-Metal Chem.* **2020**, *50*, 569–579. [CrossRef]
96. Del Buono, D.; Di Michele, A.; Costantino, F.; Trevisan, M.; Lucini, L. Biogenic ZnO nanoparticles synthesized using a novel plant extract: Application to enhance physiological and biochemical traits in maize. *Nanomaterials* **2021**, *11*, 1270. [CrossRef]
97. Abou-Zeid, H.; Ismail, G. The role of priming with biosynthesized silver nanoparticles in the response of *Triticum aestivum* L. to salt stress. *Egypt. J. Bot.* **2018**, *58*, 73–85. [CrossRef]
98. Kasivelu, G.; Selvaraj, T.; Malaichamy, K.; Kathickeyan, D.; Shkolnik, D.; Chaturvedi, S. Nano-Micronutrients [γ-Fe2O3(Iron) and ZnO (Zinc)]: Green Preparation, Characterization, Agro-Morphological Characteristics and Crop Productivity Studies in Two Crops (Rice and Maize). *New J. Chem.* **2020**, *44*, 11373–11383. [CrossRef]
99. Acharya, P.; Jayaprakasha, G.K.; Crosby, K.M.; Jifon, J.L.; Patil, B.S. Nanoparticle-mediated seed priming improves germination, growth, yield, and quality of watermelons (*Citrullus lanatus*) at multi-locations in Texas. *Sci. Rep.* **2020**, *10*, 5037. [CrossRef]
100. Batool, S.U.; Javed, B.; Zehra, S.S.; Mashwani, Z.U.R.; Raja, N.I.; Khan, T.; Alamri, S. Exogenous applications of bio-fabricated silver nanoparticles to improve biochemical, antioxidant, fatty acid and secondary metabolite contents of sunflower. *Nanomaterials* **2021**, *11*, 1750. [CrossRef]
101. Ahmed, S.; Ahmad, M.; Swami, B.L.; Ikram, S. A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications: A green expertise. *J. Adv. Res.* **2016**, *7*, 17–28. [CrossRef] [PubMed]
102. Castillo-Henríquez, L.; Alfaro-Aguilar, K.; Ugalde-Álvarez, J.; Vega-Fernández, L.; Montes de Oca-Vásquez, G.; Vega-Baudrit, J.R. Green synthesis of gold and silver nanoparticles from plant extracts and their possible applications as antimicrobial agents in the agricultural area. *Nanomaterials* **2020**, *10*, 1763. [CrossRef] [PubMed]
103. Devatha, C.P.; Jagadeesh, K.; Patil, M. Effect of Green synthesized iron nanoparticles by *Azardirachta indica* in different proportions on antibacterial activity. *Environ. Nanotech. Monit. Manag.* **2018**, *9*, 85–94. [CrossRef]
104. González-Merino, A.M.; Hernández-Juárez, A.; Betancourt-Galindo, R.; Ochoa-Fuentes, Y.M.; Valdez-Aguilar, L.A.; Limón-Corona, M.L. Antifungal activity of zinc oxide nanoparticles in *Fusarium oxysporum–Solanum lycopersicum* pathosystem under controlled conditions. *J. Phytopat.* **2021**, *169*, 533–544. [CrossRef]
105. Mishra, S.; Singh, B.R.; Singh, A.; Keswani, C.; Naqvi, A.H.; Singh, H.B. Biofabricated silver nanoparticles act as a strong fungicide against *Bipolaris sorokiniana* causing spot blotch disease in wheat. *PLoS ONE* **2014**, *9*, e97881. [CrossRef]
106. Saharan, V.; Sharma, G.; Yadav, M.; Choudhary, M.K.; Sharma, S.S.; Pal, A.; Raliya, R.; Biswas, P. Synthesis and in vitro antifungal efficacy of Cu-chitosan nanoparticles against pathogenic fungi of tomato. *Int. J. Biol. Macromol.* **2015**, *75*, 346–353. [CrossRef]
107. Abdellatif, K.F.; Abdelfattah, R.H.; El-Ansary, M.S.M. Green nanoparticles engineering on root-knot nematode infecting eggplants and their effect on plant DNA modification. *Iran. J. Biotechnol.* **2016**, *14*, 250. [CrossRef]

108. Pascoli, M.; Jacques, M.T.; Agarrayua, D.A.; Avila, D.S.; Lima, R.; Fraceto, L.F. Neem oil based nanopesticide as an environmentally-friendly formulation for applications in sustainable agriculture: An ecotoxicological perspective. *Sci. Total Environ.* **2019**, *677*, 57–67. [CrossRef]
109. Syed, B.; Prasad, M.N.; Satish, S. Synthesis and characterization of silver nanobactericides produced by *Aneurinibacillus migulanus* 141, a novel endophyte inhabiting *Mimosa pudica* L. *Arab. J. Chem.* **2019**, *12*, 3743–3752. [CrossRef]
110. Vanti, G.L.; Masaphy, S.; Kurjogi, M.; Chakrasali, S.; Nargund, V.B. Synthesis and application of chitosan-copper nanoparticles on damping off causing plant pathogenic fungi. *Inter. J. Biol. Macromol.* **2020**, *156*, 1387–1395. [CrossRef]
111. Ghazy, N.A.; El-Hafez, A.; Omnia, A.; El-Bakery, A.M.; El-Geddawy, D.I. Impact of silver nanoparticles and two biological treatments to control soft rot disease in sugar beet (*Beta vulgaris* L). *Egypt. J. Biol. Pest. Control.* **2021**, *31*, 3. [CrossRef]
112. Mishra, R.C.; Kalra, R.; Dilawari, R.; Goel, M.; Barrow, C.J. Bio-Synthesis of *Aspergillus terreus* Mediated Gold Nanoparticle: Antimicrobial, Antioxidant, Antifungal and In Vitro Cytotoxicity Studies. *Materials* **2022**, *15*, 3877. [CrossRef]
113. Sreelakshmi, B.; Induja, S.; Adarsh, P.; Rahul, H.; Arya, S.; Aswana, S.; Haripriya, R.; Aswathy, B.; Manoj, P.; Vishnudasan, D. Drought stress amelioration in plants using green synthesised iron oxide nanoparticles. *Mater. Today Proc.* **2020**, *41*, 723–727. [CrossRef]
114. Zafar, S.; Hasnain, Z.; Aslam, N.; Mumtaz, S.; Jaafar, H.Z.; Wahab, P.E.M.; Qayum, M.; Ormenisan, A.N. Impact of Zn nanoparticles synthesized via green and chemical approach on okra (*Abelmoschus esculentus* L.) growth under salt stress. *Sustainability* **2021**, *13*, 3694. [CrossRef]
115. Iqbal, M.; Raja, N.I.; Mashwani, Z.U.R.; Hussain, M.; Ejaz, M.; Yasmeen, F. Effect of Silver Nanoparticles on Growth of Wheat Under Heat Stress. *Iran J. Sci. Technol. Trans A Sci.* **2019**, *43*, 387–395. [CrossRef]
116. Kalyani, N.; Goel, S.; Jaiswal, S. On-site sensing of pesticides using point-of-care biosensors: A review. *Environ. Chem. Lett.* **2021**, *19*, 345–354. [CrossRef]
117. Jebril, S.; Fdhila, A.; Dridi, C. Nanoengineering of eco-friendly silver nanoparticles using five different plant extracts and development of cost-effective phenol nanosensor. *Sci. Rep.* **2021**, *11*, 22060. [CrossRef]
118. Thakur, M.; Wang, B.; Madan, L.; Verma, L. Development and applications of nanobiosensors for sustainable agricultural and food industries: Recent developments, challenges and perspectives. *Environ. Technol. Inn.* **2022**, *26*, 102371. [CrossRef]
119. James, A.; Franco, F.; Merca, E.M.; Rodriguez, S.; Johny, F.; Balidon-Veronica, P.; Divina, M.; Evangelyn, A.; Alocilja, C.; Fernando, L.M. DNA based electrochemical nanobiosensor for the detection of *Phytophthora palmivora* causing black pod rot in cacao (*Theobroma cacao* L.) pods. *Physiol. Mol. Plant Pathol.* **2019**, *107*, 14–20. [CrossRef]
120. Duhan, J.S.; Kumar, R.; Kumar, N.; Kaur, P.; Nehra, K.; Duhan, S. Nanotechnology: The new perspective in precision agriculture. *Biotechnol. Rep.* **2017**, *15*, 11–23. [CrossRef]
121. Giraldo, J.P.; Wu, H.; Newkirk, G.M.; Kruss, S. Nanobiotechnology approaches for engineering smart plant sensors. *Nat. Nanotechnol.* **2019**, *14*, 541–553. [CrossRef] [PubMed]
122. Lew, T.T.S.; Koman, V.B.; Silmore, K.S.; Seo, J.S.; Gordiichuk, P.; Kwak, S.Y. Real-time detection of wound-induced H_2O_2 signalling waves in plants with optical nanosensors. *Nat. Plants* **2020**, *6*, 404–415. [CrossRef] [PubMed]
123. Kaushal, M.; Wani, S.P. *Nanobiosensors: Frontiers in Precision Agriculture*; Prasad, R., Ed.; Springer Nature Ltd.: Singapore, 2017; pp. 279–291.
124. Ramnani, P.N.; Saucedo, M.; Mulchandani, A. Carbon nanomaterial-based electrochemical biosensors for label-free sensing of environmental pollutants. *Chemosphere* **2016**, *143*, 85–98. [CrossRef] [PubMed]
125. Malik, S.; Dhasmana, A.; Preetam, S.; Mishra, Y.K.; Chaudhary, V.; Bera, S.P.; Ranjan, A.; Bora, J.; Kaushik, A.; Minkina, T.; et al. Exploring Microbial-Based Green Nanobiotechnology for Wastewater Remediation: A Sustainable Strategy. *Nanomaterials* **2022**, *12*, 4187. [CrossRef] [PubMed]
126. Singh, P.; Singh, H.; Kim, Y.J.; Mathiyalagan, R.; Wang, C.; Yang, D.C. Extracellular synthesis of silver and gold nanoparticles by *Sporosarcina koreensis* DC4 and their biological applications. *Enzym. Microb. Technol.* **2016**, *86*, 75–83. [CrossRef]
127. Nazari, N.; Kashi, F.J. A novel microbial synthesis of silver nanoparticles: Its bioactivity, Ag/Ca-Alg beads as an effective catalyst for decolorization Disperse Blue 183 from textile industry effluent. *Sep. Purificat. Technol.* **2021**, *259*, 118117. [CrossRef]
128. Qiu, X.; Wang, S.; Miao, S.; Suo, H.; Xu, H.; Hu, Y. Co-immobilization of laccase and ABTS onto amino-functionalized ionic liquid-modified magnetic chitosan nanoparticles for pollutants removal. *J. Hazar. Mat.* **2021**, *401*, 123353. [CrossRef]
129. Soto-Robles, C.A.; Nava, O.; Cornejo, L.; Lugo-Medina, E.; Vilchis-Nestor, A.R.; Castro-Beltrán, A.; Luque, P.A. Biosynthesis, Characterization and Photocatalytic Activity of ZnO Nanoparticles Using Extracts of *Justicia spicigera* for the Degradation of Methylene Blue. *J. Mol. Struct.* **2021**, *1225*, 129101. [CrossRef]
130. Saini, M.; Yadav, S.; Rani, N.; Mushtaq, A.; Rawat, S.; Saini, K.; Maity, D. Biosynthesized zinc oxide nanoparticles using seed and bark extract of *Azadirachta indica* for antibacterial, photocatalytic and supercapacitor applications. *Mat. Sci. Eng. B* **2022**, *282*, 115789. [CrossRef]
131. Ramakrishna, M.; Babu, D.R.; Gengan, R.M.; Chandra, S.; Rao, G.N. Green synthesis of gold nanoparticles using marine algae and evaluation of their catalytic activity. *J. Nanost. Chem.* **2016**, *6*, 1–13. [CrossRef]
132. Balaraman, P.; Balasubramanian, B.; Kaliannan, D.; Durai, M.; Kamyab, H.; Park, S.; Chelliapan, S.; Lee, C.T.; Maluventhen, V.; Maruthupandian, A. Phyco-synthesis of silver nanoparticles mediated from marine algae *Sargassum myriocystum* and its potential biological and environmental applications. *Waste Biomass Valorizat.* **2020**, *11*, 5255–5271. [CrossRef]

133. Aboelfetoh, E.F.; El-Shenody, R.A.; Ghobara, M.M. Eco-friendly synthesis of silver nanoparticles using green algae (*Caulerpa serrulata*): Reaction optimization, catalytic and antibacterial activities. *Environ. Monit. Assess.* **2017**, *189*, 349. [CrossRef]
134. Agarwal, P.; Gupta, R.; Agarwal, N. Advances in synthesis and applications of microalgal nanoparticles for wastewater treatment. *J. Nanotechnol.* **2019**, 7392713. [CrossRef]
135. Ahmed, T.; Noman, M.; Shahid, M.; Niazi, M.B.K.; Hussain, S.; Manzoor, N.; Wang, X.; Li, B. Green synthesis of silver nanoparticles transformed synthetic textile dye into less toxic intermediate molecules through LC-MS analysis and treated the actual wastewater. *Environ. Res.* **2020**, *191*, 110142. [CrossRef]
136. Liang, Y.; Demir, H.; Wu, Y.; Aygun, A.; Tiri, R.N.E.; Gur, T.; Yuan, Y.; Xia, C.; Demir, C.; Sen, F.; et al. Facile synthesis of biogenic palladium nanoparticles using biomass strategy and application as photocatalyst degradation for textile dye pollutants and their in-vitro antimicrobial activity. *Chemosphere* **2022**, *306*, 135518. [CrossRef]