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Review Article

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Potential Applications of Nanotechnology in Agriculture: Conceptions, Characteristics, Prospects, and Limitations - A Review

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Abstract

Nanotechnology is a trending area of multidisciplinary research. It provides many opportunities in diverse field of science like chemical engineering, medicine, pharmaceuticals, environment, and agriculture. The prospective uses and advantages of nano science in agriculture are enormous. Nanomaterials have small size and distinctive physical and chemical features. Due to this, they play significant role in the different agricultural applications like seed germination, seedling growth, plant development, and plant protection. Various studies show that technology based on nanomaterials will have large and deep-rooted impact on agricultural area and crop production. Nanomaterials improve seed germination percentage rate and increase length of root and shoot with their ratio and biomass. Nanomaterials enhance biological parameters such as photosynthetic process and nitrogen metabolism in several crop plants. In the recent agricultural scenario, nanotechnology is playing a major role in crop disease management because of its environment friendly nature and potentiality. To reduce the side effects of nanotechnology on health of living organism and environment, the world is moving towards green nanotechnology. Green synthesis of metallic nanoparticles, characterization of synthesized nanoparticles, and their potential application were discussed in this review.

Keywords

Agriculture, Environment, Nanomaterials, Nanotechnology

Introduction

Agriculture plays a vital character in the economy of a nation [1]. The increase in agricultural production is important for the development of a country [2]. Gross Domestic Product growth of a nation depends on growing food production rates [3]. Several factors such as climate change, soil nutrients, temperature, moisture content of air, and water holding capacity of soil directly affect food production and agricultural growth [4]. Thus, it is essential for a country to control the adversarial factors of agriculture [5]. Government needs to provide sustainable agriculture management as constantly growing population is raising the demand for higher agricultural yields and better strategies for optimization of agricultural practice [6]. The main purpose of sustainable agriculture for society is to provide best facilities for agriculture output and textile production [7]. There has been increased in crop production, soil nutrient, nitrogen efficiency, and water absorption with the use of sustainable agriculture practices [8]. Sustainable agriculture has promoted judicious use of fertilizers, herbicides, pesticides [9], and agrochemicals in some livestock production practices [10]. Nanotechnology is a modern technology which has shown its abilities in numerous arenas like environment, solar, medicine, engineering, agriculture, and pharmaceuticals [11-13].It has been drawing attention for the last two decades and is currently being heavily used in agriculture science and medical science [14]. Nanotechnology can positively impact sustainable agriculture with maximizing crop yields with minimum use of fertilizers, pesticides, and herbicides by observing ecological variables and applying directed action [15]. It can boost the agricultural production and its quality in environmental-friendly manner by giving innovative solutions to remediate and protect ecosystem [16]. Agricultural nanotechnology is a part of agricultural science that uses nanomaterials to improve agronomic management of soil, water, crops, and food [17]. Nanomaterials may have specific surface components, various types and concentrations of sites, and varied reactivity with reference to mechanisms like adsorption and electrochemical reactions, as compared to bulk materials, which could be useful in producing nanomaterials for agricultural purpose [18]. The huge surface area provided by small nanomaterials makes them desirable for overcoming difficulties that are not resolved by other control approaches [19]. As a result, this technology promotes in the fall of environmental hazards [20]. Nanotechnology becomes popular due to its potential applications in various sectors such as agriculture, healthcare, and the ecosystem. [13]. Nanotechnology is a current scientific discipline that explores nanoscale materials [21]. Nanomaterials can be well-definite as materials which have, at least, one outer dimension of 1 - 100 nm [22]. These have many advantages in agricultural and environmental application due to their distinctive chemical, physical, optical, and magnetic composition [23] that are controlled by their unique size and shape [24].

Nanomaterials are of different shapes which can be classified on the basis of their dimensionality [25]: a) with three dimensions fall in the nanoscale range are called zero-dimensional nanomaterials [26] such as quantum dots, and nanoparticles [27], b) with one dimension in the nanoscale range are called one-dimensional nanomaterials such as nanowires, nanotubes, and nanorods [28], c) with two dimensions in the range of nanoscale are called two-dimensional nanomaterials such as bundle of nanowires, and bundle of nanotubes [29], and d) in three dimensional nanomaterials, none of the dimensions fall within the nanoscale range such as nanofilms and nanolayers [30].

Nanotechnology offers its own set of advantages and drawbacks [31]. Natural sources and industrial manufacturing both contribute to the occurrence of nanomaterials in the surroundings [32]. Nanomaterials contact the land through accumulation in the environment and rain, as well as straight delivery in agricultural areas. Plants absorb nanoparticles from the soil and nanoparticles can also enter organisms. The world is heading into green nanotechnology in order to lessen the adverse effects of nanotechnology on health of human [33] and the surroundings [34]. The combination of nanotechnology functions with green chemistry techniques become a key element of the nanotechnology future [35]. Biogenic synthesis of metallic nanoparticles includes various biogenic materials such as bacteria, fungi, algae, enzymes [36], extracts of plants, and agricultural wastes [37]. Natural products with various chemical substances perform as suitable reducing agents for the synthesis of metallic nanoparticles [38]. Green nanotechnology is required to avoid the construction of undesirable and harmful by-products through the authentic, sustainable, and environmentally friendly methods of synthesis [39]. These methods are beneficial since they are cheap, simple, and take less reaction time [40]. Green synthesis of nanoparticles includes the use of standard solvent systems and natural sources which is necessary to complete this goal [41]. Among the existing green methods to produce metal and metal oxide nanoparticles, plant extracts [42] and agricultural waste [43] are considered as one of the most favorable natural reducing agents [44]. Use of plant extracts and agricultural waste is a very simple and easy method to produce nanomaterials at large scale as compared to micro-organism mediated synthesis [45]. Nanomaterials developed using environment ecofriendly techniques can improve agriculture by improving fertilization [46], biological control agents [47], pesticide transportation of bioactive constituents to desired target locations [48], sewage treatment, and nutrient absorption in plants [49]. Additionally, they reduce the number of toxic substances out into the environment [50].

Biogenic Synthesis of Metallic Nanoparticles

Recent studies reported that top-down and bottom-up techniques are frequently used to synthesize metal and metal oxide nanoparticles [51]. The size of bulk structures is condensed to the nanometre scale in the “top-down” technique [52], whereas the molecular structure of metallic nanoparticles is formed by organizing atoms or molecules in the “bottom-up” approach [53]. For metallic nanoparticle synthesis, the top-down approach covers physical methods, whereas the bottom-up approach involves biological and chemical methods [54]. The application of high temperature, high pressure, and hazardous substances in physical and chemical methods of nanoparticle manufacturing is damaging to the environment [55]. It was reported that natural products can create a variety of distinct nanostructures [56]. Many bacteria, fungi, and plants have demonstrated the potential to synthesize metallic nanoparticles, each with their own set of benefits and drawbacks [57]. Bio reduction, also known as the green method for production of metallic nanoparticles, is a bottom-up strategy in which plant extracts or microorganisms are employed to reduce metal salts to nanometer-sized metals [58]. The nanoparticles produced with this technology are harmless and stable [59]. Nanostructures with desired shapes and composition can be produced by regulating biogenic synthesis [60]. This has attracted scientists’ attention in using natural products to synthesize nanostructures for a variety of uses.

Synthesis of Metallic Nanoparticles Using Microorganism

Recent studies have shown that numerous microorganisms can synthesize metallic nanoparticles and can be utilized and transformed to improve their performance for this purpose [61, 62] There are two types of methods for the biogenic synthesis of metallic nanoparticles from micro-organism

[63]. The first is bio reduction, which involves chemical reduction of metal ions into more stable structures biologically [64]. Many organisms are capable of metal reduction, which involves the reduction of a metal ion and the oxidation of an enzyme [65]. This method produces inert and stable metallic nanoparticles that can be securely separated from an impure sample [57]. Biosorption is the second method [66]. This method involves the attachment of metal ions from a liquid or soil sample to the organism itself, such as the cell membrane, and this method works without the need for energy [67]. The following sections will provide an overview on the synthesis of metallic nanoparticles by bacteria and fungi.

Synthesis using bacteria

Bacterial species has been widely studied as a source of metallic nanoparticles because of their abundance in the environment [68] and their capacity to adapt to extreme environmental conditions [69]. They're also rapidly growing, low-cost to grow, and simple to regulate [70]. Temperature, humidity, and incubation time may be easily controlled in bacterial growth during biogenic synthesis of metallic nanoparticles [71]. Intracellular and extracellular mechanisms have been used by bacteria to assist in the production of nanoparticles. The extracellular synthesis method has the potential of being quicker than intracellular synthesis because it wouldn't require a subsequent procedure to collect nanoparticles from microorganisms [72]. Bacteria are favored for nanoparticle production due to the minimal conditions required, flexibility of purification, and large inventory [73]. As a result, bacteria seem to be the most studied microorganisms [74]. To produce silver (Ag) metallic nanoparticles, *Bacillus mojavensis* BTCB15 [75], *Bacillus subtilis* [76] and *Pseudomonas aeruginosa* [77] bacterial species were utilized. *Bacillusendo phyticus*has been employed to make Ag metallic nanoparticles with a diameter varying between 5 and 5.5 nm in recent years [78]. *Aeromonas hydrophila*as well as *Lactobacillus* sp., on the other hand, produce copper sulphide (CuS) [65] and titanium dioxide (TiO_2) nanoparticles [79]. Gold (Au) nanoparticles were synthesized by *Micrococcus yunnanensis* [70] and *Mycobacterium* sp. [80] in recent studies while cadmium nanoparticles were synthesized by *Clostridium thermoaceticum* and *Escherichia coli.* [81]. Bacterial species can be utilized as catalysts to produce inorganic nanoparticles as well as active supporters in the synthesis of nanoparticles [82]. Bacteria can produce extracellular or intracellular nanomaterials in nutrient broth during the gestation period. As a result of this process, bacterial biosynthesis of metallic nanoparticles is a feasible, efficient, and appropriate method for manufacturing [83]. The size, synthesis method, and various applications of metallic nanoparticles produced by different bacterial species were summarized in Table 1.

Synthesis using fungi

Fungi have been used to produce metallic nanoparticles, and they are attracting a lot of attention since they have some advantages over bacteria for nanoparticle synthesis [84]. It has been reported that fungi are viable extracellular enzyme secretors, and many of their species grow quickly, making laboratory culturing and storage simple [85]. As a result, fungus can produce metal nanoparticles and nanostructures either intracellularly or extracellularly by using reducing enzymes [86]. One of several key benefits of extracellular production of metal and metal oxide nanoparticles by fungus is the appearance of a huge number of enzymes in a freed and purified condition that can be applied directly for downstream preparation [87]. The simplicity of scaling up and downstream processing, financial sustainability, and the presence of myce-

Table 1: Synthesis of metallic nanoparticles using bacteria.

Bacterial Species	Metallic nanoparticles	Size (nm)	Synthesis method	Application	References
Pseudomonas aeruginosa	Ag	50 - 85	Extracellular	Antibacterial activity	[77]
Bacillus subtilis	Ag	3 - 20	Extracellular	Antibacterial activity	[76]
Pantoea ananatis	Ag	8.06 – 91.31	Extracellular	Antimicrobial activity	[74]
Bacillus endophyticus	Ag	5.1	Extracellular	Antimicrobial activity	[78]
Bacillus mojavensis BTCB15	Ag	2.3	Extracellular	Antimicrobial activity	[75]
Shewanella loihica PV-4	Cu	10 - 16	Extracellular	Antibacterial activity	[63]
Shewanella loihica PV-4	Pd	4 - 10	Extracellular and intracellular	Catalytic Activity	[61]
Shewanella loihica PV-4	Pt	2 – 7	Extracellular	Catalytic Activity	[83]
Micrococcus yunnanensis	Au	53.8	Extracellular	Cytotoxic activity and antibacterial activity	[70]
Mycobacterium sp.	Au	5 – 55	Extracellular	Anticancer activity	[80]
Bacillus megaterium NCIM2326	ZnO	45 – 95	Extracellular	Antimicrobial activity	[69]
Halomonas elongata IBRC-M 10214	ZnO	18.11	Extracellular	Antibacterial activity	[73]
Acinetobacter schindleri SIZ7	ZnO	20 - 100	Extracellular	Antimicrobial activity	[64]
Aeromonas hydrophila	CuS	200	Extracellular and intracellular	Antibacterial, anti-inflammatory, and antioxidant activity	[65]
Bacillus cereus MN181367	ZnO	58.77 - 63.3	Extracellular	Antibacterial activity	[68]

lia, which gives a bigger surface area, were discovered to be all important concerns [88]. Fungi-derived nanoparticles could be employed in the delivery of drugs [89], treatment for cancer [90], MRI and medical image processing [91], and other applications. Fungi-based nanoparticle synthesis is an innovative, cost-effective, and environmentally acceptable method [92]. In the past few years, a range of different fungi have been used to make metallic nanoparticles [93]. For example, *Rhizopus stolonifera* [94], *Rhodotorula glutinis*, and *Arthroderma fulvum* [95] fungal species were used to make Ag metallic nanoparticles. In recent times, *Colletotrichum* sp. has been used to generate metallic nanoparticles of aluminium oxide (Al_2O_3) by an extracellular method with a diameter ranging from 30 to 50 nm [96]. In recent investigations, *Aspergillus niger* and *Candida albicans* [97] synthesised zinc oxide (ZnO) nanoparticles, while *Penicillium chrysogenum* [98] and *Pleurotus ostreatus* [99] synthesised magnesium oxide (MgO) and Au nanoparticles. The *Fusarium oxysporum* fungus is linked to the synthesis of Au metallic nanoparticles with an ideal size of about 20 nm and a sphere-shaped shape [100]. Kobashiwaga et al. published the biogenic production of Ag nanoparticles using the lignolytic fungus *Trametestrogii.* And after 20 days, adding Ag salt of nitrate to the fungal solution does not lead to the formation of Ag metallic nanoparticles. However, under an alkaline pH of 13, the production of Ag nanoparticles is more durable for 72 hours due to the electrostatical adsorption of hydroxides on Ag nanoparticles [101]. Purified organic extracts of *Aspergillus terreus* [102] and *Aspergillus niger* [103], isolated from a medicinal plant, could be used to build a sustainable and environmentally friendly fungus nanofactory [104,105]. *Trichoderma viridae* was utilized to prepare a quick and environmentally benign technique of synthesizing metallic nanoparticles by generating secondary metabolites at high temperature [106,107]. The size, synthesis method, and various applications of metallic nanoparticles produced by different fungal species were summarized in Table 2.

Synthesis of Metallic Nanoparticles Using Plant Extract

Over the last decade, there has been an increase in studies into the biogenic synthesis of metal [108] and metal oxide nanoparticles [109] utilizing plants or plant extracts. For nanoparticle synthesis, techniques such as thermal evaporation, reduction using mild chemicals [110], photochemical reagents [111], and electrochemical reagents has mostly been used [112]. Although all these techniques are capable of generating nanoparticles, they have a number of drawbacks [113], including the high cost of the process and the fact that they are not eco-friendly due to the use of hazardous solvents and reductants [114]. Even though chemical modifiers are consumed more than plant extracts, these substances are toxic to the environment and have health impacts [115]. Green chemistry techniques are used to synthesize nanoparticles that are easy, accessible, less energy-intensive [116], eco-friendly, minimize the use of hazardous components [117], and improve the efficiency of the process to avoid these problems [118]. Polyphenolic compounds obtained from natural sources seem to be the most enormous organic antioxidants [119], with huge potential as medicines, vitamins, and dietary supplements [120]. The polyphenols present in plant components act as biological reducing agents as well as nanoparticle fixers, which is the basic principle in green synthesis techniques [121]. Plant components, including flowers, leaves, roots, and stems, have been actively used for biogenic synthesis due to

Table 2: Synthesis of metallic nanoparticles using fungi.

Fungal species	Metallic Nanoparticles	Size (nm)	Synthesis Method	Application	References
Rhizopus stolonifer	Ag	5 - 50	Extracellular	Anticancer	[88]
Trichoderma longibrachiatum	Ag	10	Extracellular	Antimicrobial activity	[92]
Aspergillus terreus	Ag	16 - 57	Extracellular	Antibacterial activity	[102]
Rhodotorula glutinis	Ag	15.45	Extracellular	Antifungal activity, and cytotoxicity	[66]
Arthroderma fulvum	Ag	15.5	Extracellular	Antifungal activity	[95]
Fusarium oxysporum	Ag	5 – 13	Extracellular	Antibacterial and antitumor activity	[93]
Trichoderma harzianum	Ag	20 – 30	Extracellular	Antifungal activity	[106]
Cladosporium cladosporioides	Ag	100	Extracellular	Antibacterial and antioxidant activities	[86]
Pleurotus ostreatus	Au	10 – 30	Extracellular	Antimicrobial and anticancer	[90]
Aspergillus niger	Ag	10 - 100	Extracellular	Antifungal activity	[103]
Penicillium chrysogenum	MgO	7 – 40	Extracellular	Antimicrobial activity	[98]
Aspergillus niger	ZnO	80 – 130	Extracellular	Therapeutic application	[91]
Candida albicans	ZnO	25	Extracellular	Synthesis of pyrazolins	[97]
Fusarium keratoplasticum strain	ZnO	10 – 42	Extracellular	Antibacterial and antioxidant activities	[84]
Colletotrichum sp.	Al_2O_3	30 – 50	Extracellular	Antimicrobial activity	[96]

the high-quality phytochemicals they generate [122]. In the biopharmaceutical fields, metallic nanoparticles of Ag can be extracted from medicinal herbs, including *Saccharum officinarum, Cinamomum camphora, Oryza sativa, Medicago sativa,* and *Magnolia Kobus* [123]. The first work reported on Au nanoparticle synthesis employed geranium leaf extract as a capping and reducing agent. The terpenes in leaf extract were responsible for the reduction of Au ions to Au nanoparticles. These nanoparticles were said to be created in different shapes, including spherical, triangular, and decahedral **[**124**].** *Gardenia jasminoides, Anogeissus latifolia, Glycine max, Musa paradisica, Doipyros kaki,* and other plant extracts have been used in the biogenic production of palladium (Pd) and platinum (Pt) metallic nanoparticles [125]. Metallic nanoparticles of Cu [126] are prepared by reducing Cu salt with different plant extracts, like flower extracts of *Aloe vera*. Metallic oxide nanoparticles of tin [127] and titanium [128] were manufactured with an environmentally sustainable approach from the roots of Rheum emodi, a Himalayan herb that has gained a lot of interest in the medical field**.** Goutam et al. constructed metallic nanoparticles of TiO_2 from *Jatropha curcas* leaf extract [129], which has been confirmed by UltraViolet-Visible (UV-Vis) spectrophotometer, fourier transform infrared (FTIR) spectroscopy, and X-ray diffraction (XRD). Other studies suggest that plant extracts, rather than microbes, can be used to rapidly synthesize highly stable nanoparticles. A current study describes an environmentally friendly approach for biogenic synthesis of ZnO nanoparticles utilizing *Cassia renigera* bark extract, as well as an assessment of its impact on four rice cultivars (PR 7, basmati 1509, HR 47, and sharbati) [130]. The lack of pathogenicity is a key benefit of employing plants instead of bacteria or fungus to produce metallic nanoparticles [131]. As a result, the plant extract could be used in an appropriate mechanism for reducing and stabilizing metallic nanoparticles [132]. The size, morphology, and various applications of metallic nanoparticles produced by different plant extract were summarized in Table 3.

Synthesis of Metallic Nanoparticles Using Agricultural Waste

Agricultural waste is produced in hundreds of millions of tons per year [133]. It was reported that unlike other industrial wastes, it has a relatively pure composition [134] and does not contain highly hazardous components [135], resins [136], or other additives [137], which limits its potential for reuse in the environment [138]. In recent studies, it has been shown that various biotechnological procedures [139] have been developed to use agro-wastes to increase nutritional quality through solid state fermentation [140], enzyme production, organic acid production [141], and as renewable resources for biogas production [142]. It has been reported that the use of agro-wastes as biomolecule sources in green nanotechnology has got a lot of attention, with various agro-wastes being recorded for their potential in nano biotechnology [143]. In general, extracts containing active biomolecules that catalyze the creation of nanoparticles can be produced from dried and ground agro-waste materials [144] using a simple hot water extraction process. In the green synthesis of metal and metal oxide nanoparticles, plant secondary metabolites operate as stabilizing and reducing agents and used to make nanoparticles of metal oxides such as Zn [145], Au [146], and Pd [147]. The synthesized metallic nanoparticles were characterized by a UV–Vis spectrophotometer. Distinctive method for the biogenic synthesis of Ag metallic nanoparticles via agricultural waste has been reported recently [148]. They used an aqua mushroom extract of *Pleurotus giganteus* in $AgNO_3$ solution. Metallic nanoparticles of Ag are generated in a controlled manner in 3 – 4 hours at room temperature. Synthesized

Table 3: Synthesis of metallic nanoparticles using plant extract.

Plant Extract	Metallic nanoparticle	Size (nm)	Morphology	Applications	References
Morus alba L.	Ag	80 - 150	Spherical	Antibacterial activity	[42]
Beta vulgaris L.	Ag	20 - 50	Spherical	Anticancer activity	[108]
Piper longum	Ag	15 - 40	Spherical	Catalytic and antibacterial activity	[110]
Cocos nucifera	Ag	22	Spherical	Antimicrobial activity	[52]
Emblica officinalis	Ag	15	Spherical	Antibacterial activity	[54]
Abelmoschus esculentus	Au	45 - 75	Spherical	Antifungal activity	[116]
Eucommia ulmoides	Au	16.4	Spherical	Catalytic activity	[59]
Morinda citrifolia	Au	12.17 – 38.26	Spherical	Anticancer activity	[115]
Solanum nigrum	Au	50	Spherical	Antibacterial activity	[113]
Zingiber officinale	Au	5 – 15	Spherical	Biomedical	[131]
Aloe barbadensis	CuO	15 – 30	Spherical	Nanomedical	[126]
Gloriosa superb	CuO	5 - 10	Spherical	Antibacterial activity	[109]
Punica granatum	Fe_3O_4	12.6	Spherical	Water purification	[60]
Cassia fistula	ZnO	5 - 15	Spherical	Photocatalyst, and antioxidant	[119]
Moringa oleifera	ZnO	24	Spherical	Photocatalytic activity	[132]

nanoparticles were spherical in shape, with an average particle size of 20 nm. Fruit husk of *Nypa fruticans*, a harmless, environmentally safe biological resource, was used to successfully produce metallic nanoparticles of Au. The synthesis process rate is relatively faster than that of other natural products. The synthesized Au nanoparticles were characterised by transmission electron microscopy (TEM), UV-Vis spectrophotometer, and XRD. In a study, rice bran was used as a precursor in the production of ZnO nanoparticles [149]. Rice bran is a cost-effective and biological precursor for Zn nanoparticles production among the suitable agricultural wastes. TEM was used to analyze the structure and morphology of the produced metallic nanoparticles. The production of metallic Ag nanoparticles was investigated by utilizing *Cocos nucifera* mesocarp layer extract [150]. When $AgNO_3$ solution was reacted with a dilute extract of *C. nucifera* coir at 60 ˚C, Ag ions were reduced. The activation of surface plasmon resonance using UV–Vis spectrophotometer [151] at 433 nm was used to confirm the synthesized Ag metallic nanoparticles. Sinsinwar et al. suggested that extracts from agricultural wastes were utilized as reducing and stabilizing agents for their syntheses in the majority of cases [152], with a wide range of actions ranging from antibacterial, antifungal, insecticidal, catalytic, and cytotoxicity against cancer cells. Because of its biomedical applications, nontoxicity, ecological approach, and green chemistry nature, phyto-synthesis of transition metal nanoparticles is getting more popular. The size, morphology, and various applications of metallic nanoparticles synthesized from agricultural waste were summarized in Table 4.

Characterization of Metallic Nanoparticles

Nanomaterials have indeed been explored using such several techniques to detect their dimensions, morphology, crystallographic, chemical compositions, and other physical characteristics [153]. In many areas, physical aspects can indeed be assessed using more than one technique [154]. Size and shape are two of the most important criteria addressed in the characterization of nanoparticles [155]. Researchers also could analyze the surface morphology and estimate the size distribution, surface charge density, quantity of accumulation, and surface area [156]. Various approaches for characterization are classified focused on the technology's concept, the insights it may offer, and the components it is suitable for [157]. These characterization techniques are sometimes used specifically to investigate a specific parameter, while other times they are combined [158]. The thickness, concentration, and ligands present on the interfaces of nanostructures may affect their additional areas of characterization [159]. There are two types of major techniques that are widely used for the characterization of nanomaterials. The first is spectroscopic and the other one is microscopic.

Spectroscopic techniques

Many spectroscopic techniques are used for the characterization of metallic nanoparticles, out of which XRD is most used technique [160]. XRD normally gives information about the structure, nature, parameters, and size of the crystal [161]. In XRD measurement, the crystal parameter is calculated through using Scherrer equation, which is focused on

Table 4: Synthesis of metallic nanoparticles using agricultural waste.

Agricultural waste	Metallic nanoparticle	Size (nm)	Morphology	Application	References
Watermelon rind	Pd	96	Spherical	Catalytic activity	[147]
Lansium domesticum fruit peel	Au	20 - 40	Triangular and hexagonal	Biomedicine	[124]
Acacia gum	MgO	<100	Spherical	Divalent metallic species removal from water	[136]
Grape waste	Au	20 - 25	Spherical	Biological applications	[137]
Banana peel extract	Ag	23.7	-	Antibacterial activity	[141]
Mushroom Extract of *Pleurotus giganteus*	Ag	2-20	Spherical	Therapeutic applications	[148]
Waste coconut husk	ZnO	10 - 100	Spherical	Photocatalytic activity	[138]
Orange peels	ZnO	30 - 100	Spherical	Antibacterial activity, antioxidant activity, and anticancer activity	[145]
Mandarin waste peels	Ag	10 - 19	Spherical/ Oval	-	[140]
Rice bran	ZnO	17.16	Spherical	Antibacterial activity	[149]
Hybrid grape pulp extract	ZnO	23.56	Irregular hexagonal	Photocatalytic degradation activity	[135]
Corn cob	Au	35	Spherical	Antibacterial activity	[139]
Passiflora edulis peels	Au	7	Spherical	Antibacterial effect and catalytic activity	[134]
Nypa fruticans fruit husk	Au	15 - 20	Spherical	Antibacterial activity	[146]
Pomegranate (*Punica granatum*) Extracts	ZnO	32.98	Spherical and hexagonal-shaped	Antibacterial Activity	[133]

the broadening of a sample's peak intensity [162]. Using X-ray line broadening, Holder et al. calculated the standard size of the crystal of metallic nanoparticles, which was found to be between 9 and 53 nm [163]. There are several different techniques that may be used to determine the basic characteristics of metallic nanoparticles like size, shape, structure, and composition. Another major analytical approach for determining the molecular structural properties of nanomaterials is nuclear magnetic resonance spectroscopy [164]. In recent studies, it has been reported that it is based on the phenomenon that occurs when spin active nuclei are positioned in a high external magnetic field, resulting in a slight energy divergence within the down and up spin states [165]. Xiang et al. published a detailed article about NMR techniques in novel metallic nanoparticles. It was explained that characterization of nanoscale materials is also done using the BET approach, named after the developers' surnames initials, Brunauer, Emmett, and Teller, and founded on the principle of the adsorption process of a gaseous phase on a solid surface [166]. It's used to find out the surface area of nanomaterials, and it's a rather precise, quick, and simple method for doing so [167]. UV-Vis spectrophotometer is yet another popular characterization approach for nanostructures that is both simple and inexpensive [164]. It measures the light output emitted by a substance in relation to the amount of light emitted by a reference material. R Begum et al. inferred that UV-Vis spectrophotometer is a useful method for identifying, investigating, and evaluating the stability of nanoparticle colloidal solutions because the optical properties of nanoparticles are affected by their dimension, morphology, quantity, and refractive index [168].

Microscopic techniques

An important technique that is used to characterize the construction of different nanocomposites that can be similar in structure to numerous crystal systems is TEM [164]. It was reported that TEM is an important microscopy technology that can utilize advantage of the interaction between an electron beam with a constant current density and a sample. The amount of the interaction is determined by several factors, including sample size, density, and composition of element. The information obtained from the transmitted electrons is used to create the final image. An important technique for analyzing the morphology and structure of nanomaterials is the scanning electron microscope (SEM). In this technique, a low-energy beam of electrons is projected onto the substance and analyses the substance's surface. As the electron beam penetrates and hits the material, a number of interactions occur, resulting in the emission of electrons and protons from the surface of the sample. Sundar et al. employed a high-resolution SEM to visualize Au nanoparticles in tissues and cells [169]. This approach ensures the simple viewing of metallic nanoparticles, and preparation of sample is quick and painless. According to Gemmi et al., electron diffraction also known as selected area electron diffraction, is another fundamental microscopy technique for investigating the crystalline structure of nanoparticles [170]. Various parameters of metallic nanoparticles and their characterization techniques were summarized in Table 5.

Role of Nanotechnology in Agriculture

Due to the restricted resources of petroleum fuels and natural gas, the cost of raw materials such as synthetic fertilizers and pesticides is predicted to rise at an alarming rate [3]. A precision agricultural method is a more suitable substitution to lessen the cost of crop production and improve output [4]. Because of advancements in nanotechnology, a variety of methods for remodeling precision agricultural practices are now available, allowing effective control at the nanoscale [171]. In nanotechnology, agrochemical exhibits amazing qualities at the nanoscale that bulk materials do not [6]. Nanoscience can also improve the genetic code of plants by transporting chemical molecules and proteins to exact locations at the cell surface [31]. Excessive and improper use of pesticides and fertilizers in conventional methods has increased chemicals and pollutants in surface and groundwater [7], resulting in increasing healthcare and water purification expenditures as well as a reduction in fisheries and recreational areas [21]. The disadvantages of conventional technologies can be seen in the fact that proponents of alternative farming, such as "agricultural production", propose environments that are neither unique nor effective because farming operates in an open process, making conservation agriculture thermochemical unviable. With the use of nanomaterials, traditional fertilizers have been replaced by nanoscale fertilizers [14]. Nano-fertilizers tend to enhance soil fertility and assist in the reduction of anaerobic decomposition and environmental contamination [15]. Nowadays, the research technology development process seems to have the capability to increase agricultural efficiency, productivity, and quality of products and hence nutritive value [20]. In developed countries, nano-based biosensors and agrochemicals for agricultural applications are all being used. Nano-sensors, which could diagnose organic pollutants and pathogens, and nano-delivery processes that would accurately release the drug at the right time, are among the applications expected for food and agriculture [172].

Table 5: Characterization techniques for different parameters.

Parameters	Characterization techniques	References
Detection of nanoparticles	TEM, SEM, STEM, and magnetic susceptibility	[160]
Size and shape of nanoparticles	TEM, XRD, HRTEM, AFM, EPLS, FMR, and 3D-tomography	[157]
Crystal structure	XRD, HRTEM, electron diffraction, and STEM	[166]
Surface area and charge	BET, liquid NMR, Z-potential, and EPM	[162]
3D visualization	3D-tomography, AFM, and SEM	[164]
Optical character	UV-Vis spectrophotometer	[154]

Applications of Nanotechnology in Sustainable Agriculture

Nanotechnology has recently been proven to have the ability to revolutionize the agriculture sector by increasing the efficiency of agriculture products [10] and providing solutions to environmental and agricultural challenges to improve food production and sustainability, according to recent studies [2].

To fulfill the demands of a growing population, nanoscience uncovers a broad range of unique functions in the sector of food and agriculture [8]. Nanotechnology has a wide range of applications, including the use of agricultural resources such as nutrients, chemicals, and water in agricultural processes [5]. Nanoparticles have also proven to be effective in the field of crop biotechnology, where they have been used to protect agricultural crops [1]. Different uses of nanomaterials in agriculture are thoroughly evaluated in this review, including nano-fertilizers, nano-pesticides, nano-biosensors, and nanomaterials for soil remediation via biotic and abiotic pathways (Figure 1).

Nano-biosensors

Nano-biosensors serve as a steppingstone for basic research and provide instruments for authentic bio-analytical applications that were previously unattainable [4]. Nano-biosensors are nano-sensors immobilized with bioreceptors that are unique to the chemicals of interest [173]. A nano-biosensor is a device that uses nanotechnology to detect and evaluate data at the atomic level [6]. Biologically activated elements, a transducer, and a detector are the three main components of a nano-biosensor [174]. Neurotransmitters, proteins, antibodies, nucleotides, chemical impressions, and tissue that receive signals from the sample components and send them to the transducer are examples of biologically sensitive elements [47]. The transducer serves as an intermediary, monitoring the physical change caused by the reaction at the bioreceptor and converting that energy into a detectable electrical output [7]. The detector component captures the transducer's signals, which are then magnified and evaluated by a microcontroller before being transferred to a computer [175]. Nano-biosensors are currently fulfilling their potential application in agriculture. These provide accurate and timely information about the crop and its field condition with crop growth [176]. Excessive use of pesticides and fertilizers can also be reduced by real time monitoring which is useful in the decrease of ecological defect and manufacturing cost [11]. Nano-biosensors are also used to manage soil nutrients and to reduce pollution in the environment [177]. Nano-biosensors have various advantages, including increased sensitivity, which reduces the reaction time for detecting plant pathogens in crops, hence speeding agricultural productivity and minimizing food safety concerns [15]. These are useful in the detection of the humidity of soil, residue of pesticide, and concentration of nutrients [178]. These sensors are extremely sensitive, enable to detect single virus particles or extremely low amounts of a potentially dangerous material [179]. The traditional methods of agriculture are converting into smart methods using nano-sensors which are environment friendly and more efficient in term of energy for the sustainable agriculture [180]. Various types of nanomaterials can be used to make nano-biosensors such as quantum dots carbon nanotube Au nanoparticles and different nanocomposites with their polymer [181]. These are highly sensitive due to their large surface area. These showed quick response in seconds which is reliable and more stable [182]. Nano-biosensors have a lot of potential above regular biosensors right now [17]. These have distinct advantages, such as increased detection sensitivity, and have enormous potential for use in a variety of fields, including environmental and biological process regulation, food quality control, agriculture, biosafety, and most notably therapeutic applications.

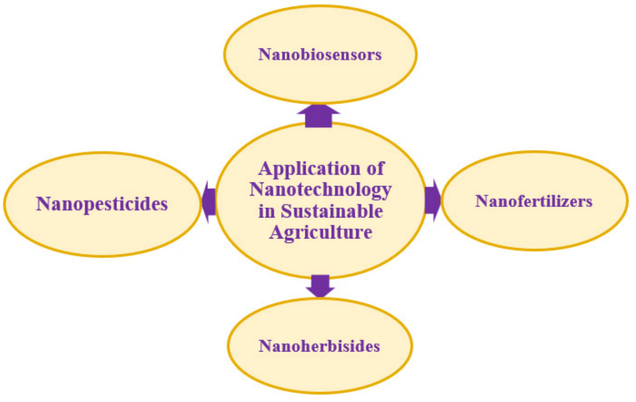

Figure 1: Application of nanotechnology in sustainable agriculture.

Nano-fertilizers

At present, conventional chemical fertilizers are being used by different methods to increase the productivity of the crop [18]. However, less than half of the chemical fertilizer used by the crop and the remaining quantity fixed inside the soil layers that cause soil pollution [183]. Chemical fertilizers are used repeatedly, due to which the fertility of the soil decreases as well as it loses the soil nutrient which are necessary for growing any crop [46]. Nanotechnology can adapt fertilizer manufacturing to the desired chemical composition, increase nutrient use efficiency while reducing environmental impact, and increase plant output [184]. A nano-fertilizer is a nutrient-delivery device that works in one of three different ways [185]. The nutrients could be enclosed inside nanomaterials such as nanoporous materials or nanotubes, wrapped in a thin polymeric membrane or supplied as nano nutrients [186]. In nano-fertilizers, nutrients are bonded to nano-sized adsorbents that distribute nutrients more gradually than conventional fertilizers, whether applied alone or in combination [187]. This method not only improves fertilizer utilization, but it also reduces nutrient loss into groundwater [188]. It can also be utilized to improve abiotic stress tolerance, and when combined with microorganisms, they provide even greater benefits [189]. Nano-fertilizers are made up of a variety of nanomaterials such as metals, oxides of metals, C-based compounds, and any other nanostructured elements, with various compositions and characteristics [190]. It can be made in a variety of ways, including top-down-a physical method, bottom-up-a chemical method, and other biological methods [19]. After years of scientific research based on particular nutrients, it has always been possible to develop different types of nano-fertilizers, such as micro-nutrient nano-fertilizers, macro-nutrient nano-fertilizers, and nanomaterial-enhanced fertilizers [191]. To reduce nutrient losses, present nano-sized formulations of nano-fertilizers improve solubility, diffusion of insoluble elements, bioavailability, and transparency of definite distribution [192]. Studies suggested that different nanoparticles such as Fe, Cu, Fe_2O_3, TiO_2, ZnO, and CeO_2 can be used as nano-fertilizers [193]. At present, nano-fertilizers are being seen as a promising alternative in agriculture as well as being considered better in every respect than conventional fertilizers [13]. Thus, based on the facts above, we can conclude that the use of nano-fertilizers increases the effectiveness of micro and macro elements, lowers soil toxicity, and reduces the frequency with which traditional fertilizers are applied.

Nano-pesticides

Nano-pesticides are two to three-dimensional nanostructures with dimensions ranging from 1 to 200 nm that are used to transport agrochemical chemicals [48]. When compared to basic pesticides, putting agrochemical into nanoparticles offers advantages due to their specific features [32]. These pesticides formulated in nanomaterials for agricultural uses, whether particularly fixed on a hybrid base, enclosed in a matrix, or complexed nanocarriers for external stimulation or enzyme-mediated reactions [194]. Nanosized particles, in combination with their shape and specific features, are expected to investigate pesticide actions in nanocarrier novel formulations based on a variety of materials, including silica, fats, polysaccharides, co-polymers, porcelain, metals, charcoal, and others [195]. Nanopesticide compositions can improve solubility in water, absorption, and preserve agrochemicals from degradation in the environment, reinventing disease, weed, and insect control in crops [34]. The neurotoxicity and genotoxicity of nanomaterials, on the other hand, are on the edge [196]. Use of traditional pesticides that is uncontrolled and illogical disrupts the ecosystem's balance and puts everyone's life in danger [197]. An acute and chronic adverse effect of industrial or unintentional absorption of pesticide residues from food, water consumption is lethal [198]. Adolescents are more sensitive to pesticides and are more likely to suffer irreversible tissue and organ damage as a result [199]. The cerebral and peripherical neurotoxic effects, as well as the effect on blood coagulation capacity, are all valid reasons to be concerned [200]. Nano-pesticides from industrial and agricultural sewage runoff enter the water supply by soil penetrating seeping after a precipitation event, changing its quality, enhancing human exposure time, and raising issues for the ecosystem [201]. Nanotechnologies strive to limit the uncontrolled and harmful use of traditional pesticides while also ensuring their safe application [20]. The most significant technological development for the safe use of pesticides and innovative ideas to supply nano-pesticides novel material is grafted intended nanoparticle compositions for ecological stimulations.

Nano-herbicides

Weeds are a major hazard in agriculture, as they drastically impair productivity. As a result, there is no choice except to eliminate them [9]. Nanotechnology can eliminate weeds in an environmentally acceptable manner by using nano-herbicides that do not leave hazardous residues in the soil or environment [12]. If the active component is paired with a "smart" delivery method, less herbicide will be utilized [35]. Because they are nanoscale in size, they will blend in with soil particles and hinder the growth of weed species that have developed resistance to traditional herbicides [23]. Herbicides on the market are designed to control or kill the weed plants above-ground parts [33]. Generating a specific herbicide component coated with nanoparticle that enters the root system of target weeds and translocate to sections that impede glycolysis of food stores in the root system, causing the specific weed plant to go starved and die [37]. Since they are target-specific, nanoparticles may indeed be able to destroy weeds and enhance yields. There are also restrictions in place for the regulated release of herbicides, which limit human damage [36]. Herbicides such as ametryn, triazine, and atrazin have all been nano-encapsulated to achieve an effective plant absorption capacity of 84% [188]. Atrazine is a pesticide that is commonly used to destroy weeds and unwanted grass that grows near farms [202]. The adsorptive stripping voltammetry process was developed to synthesise the herbicide fenclorim using carbon nanotubes at pH 4 and adsorption tactics on the electrodes [203]. Herbicide use depletes soil minerals over time and renders crops resistant to herbicides. Nevertheless, utilizing modified silver with nanoparticles and carboxymethyl cellulose facilitates herbicide breakdown [41].

Conclusions

In agriculture, nanotechnology has a variety of applications such as nano-fertilizers, nano-biosensors, nano-pesticides, etc. These are effective tools for smart agriculture systems because of their nanoscale-controlled release and site-specific delivery which overcome the side effects of conventional methods. Nano-sensors have demonstrated the ability to detect leftover pesticides, ensuring consumer food safety which is an advantage over to traditional methods. The application of metallic nanoparticles may improve the yield and development of crop plants, but the outcomes vary according to the species of plants. To understand the outcome of nanomaterials in the ecosystem, a long-term assessment of each crop-nanoparticles system is required. Within concentration levels, certain metal and metal oxide nanoparticles improved seed germination percentage, shoot and root elongation, biomass production, and plant development. Metallic nanoparticle screening and modification for numerous species of plants is needed for the commercialization of nanotechnology. The efficiency and utility of nanoparticles can indeed be controlled by modifying their compositions and durability. Over to conventional methods more research is needed to determine the expected level for each crop system.

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