Journal of
Food Chemistry & Nanotechnology

https://doi.org/10.17756/jfcn.2025-s2-006

Research Article

Open Access

Green Synthesis of Metal Oxide Nanoparticles and Their Applications in Food Packaging, Processing, and Agriculture: A Critical Review

Shyam Ajudiya[1*], Payalkumari Savaliya[1], Sahil Rawal[2], Rakesh Parmar[2], Dhruv Sardhara[2], Nitingiri Gosai[2] and Ashish Tanna[1]

[1]*Deparment of Physics, School of Science, RK University, Gujarat, India*
[2]*Department of Nano Science and Advanced Materials, Saurashtra University, Gujarat, India*

[*]Correspondence to:
Shyam Ajudiya
Department of Physics,
School of Science,
RK University,
Gujarat, India.
E-mail: shyamajudiya2003@gmail.com

Received: April 26, 2025
Accepted: June 27, 2025
Published: July 04, 2025

Citation: Ajudiya S, Savaliya P, Rawal S, Parmar R, Sardhara D, et al. 2025. Green Synthesis of Metal Oxide Nanoparticles and Their Applications in Food Packaging, Processing, and Agriculture: A Critical Review. *J Food Chem Nanotechnol* 11(S2): S54-S63.

Published by United Scientific Group

Abstract

A sustainable, environmentally responsible, and financially feasible substitute for traditional nanoparticle (NP) synthesis techniques that frequently demand dangerous chemicals, significant energy inputs, and non-renewable resources is green synthesis, which is based on the ideas of green chemistry. This method uses biological organisms as natural reducing and stabilizing agents to create metal and metal oxide NPs (MONPs), including bacteria, fungi, algae, and plant extracts. These physiologically mediated processes improve control over NP size, shape, and biocompatibility while simultaneously lowering environmental toxicity. A wide range of industries, including food technology, agriculture, environmental remediation, and medicine, use green-synthesized NPs. While NPs help with intelligent packaging, preservation, and real-time safety monitoring using nano-sensors in the food business, they also enhance nutrient delivery, disease management, and soil remediation in agriculture. Problems such possible toxicity, NP migration, and regulatory uncertainty still exist in spite of their benefits. Green synthesis, however, has great potential to advance sustainable nanotechnology by resolving the significant drawbacks of conventional synthesis techniques and bringing industrial innovation and environmental stewardship into harmony.

Keywords

Green synthesis, Nanoparticles, Metal oxide, Food technology, Agricultural applications

Introduction

Green synthesis, also known as green chemistry, is a movement towards greener and more environmentally friendly strategies in chemical manufacturing and material synthesis. Unlike conventional chemical procedures, which tend to involve toxic chemicals, poisonous solvents, and energy-consumptive processes, green synthesis endeavors to eliminate or reduce the use of harmful chemicals, lower energy intake, and utilize renewable resources [1, 2]. Conventional chemical procedures are likely to produce high levels of waste, pollution, and toxic by-products, which represent major environmental threats [3]. Green chemistry instead focuses on the design of chemical reactions that are both economically sound and environmentally friendly [4]. The fundamental concept of green synthesis is to reduce the environmental impact of industrial processes without the sacrifice of efficiency and efficacy. These include minimizing the use of toxic or dangerous solvents, substituting toxic reagents with less toxic, renewable substitutes, and process design for maximum utilization of raw materials with minimized waste generation and overall chemical production sustainability [5]. The origin of green synthesis dates back to the 1990s when there was widespread concern regarding pollution, resource losses, and hazards posed by hazardous chemicals in industries, leading to a demand for cleaner, greener alternatives. The Bhopal gas tragedy in 1984 was one of the benchmark events that revolutionized the field of green chemistry by revealing the devastating effects of uncontrolled chemical processes. This tragedy brought into focus the necessity for improved safety regulations, cleaner technologies, and more responsible industrial practices. In reaction to such issues, Paul Anastas, a prominent green chemistry figure, introduced the term "green chemistry" in 1991. With John Warner, Anastas formulated the 12 Principles of Green Chemistry in 1998 [6] which offered a guideline for directing the design and execution of sustainable chemical processes. These guidelines place a focus on ideas like atom economy (optimal utilization of raw materials), waste avoidance (prevention of the formation of toxic by-products), use of safer solvents and auxiliaries, and energy efficiency. These guidelines went on to serve as the cornerstone for green synthesis, providing a systematic method to minimize the ecological footprint of chemical manufacturing.

Green synthesis has become increasingly popular over the last few years as it can address global issues like pollution, resource loss, and climate change. It has been used in numerous applications in the fields of nanotechnology, pharmaceuticals, material science, and agriculture. For example, in the process of synthesizing NPs, plant extracts, microbes, and other natural sources are being widely employed as reducing or stabilizing agents, taking the place of poisonous chemicals used in the process in the past [7]. Not only has this ensured NP production to be environmentally cleaner, but it has also led to greener routes for producing electronics, sensors, and biomedical devices [8]. In the field of pharmaceuticals, the principles of green chemistry are being utilized to decrease dependence on hazardous solvents and reagents and thus make drug manufacturing safer and greener [9]. In agriculture, green synthesis is used to formulate environmentally friendly biodegradable pesticides and fertilizers that are less toxic to the environment [10]. A variety of methods for raising food quality and flavor are made possible by nanotechnology. Techniques for nanoencapsulation have been widely employed to enhance taste release and retention as well as provide culinary balance [11]. Nanosensors assist in the detection of any changes in the food's color as well as the production of any gases brought on by rotting. Gases like hydrogen, hydrogen sulphide, nitrogen oxides, sulphur dioxide, and ammonia are often detected by the sensors [12]. Finally, green synthesis is in line with the increasing worldwide need for more environmentally friendly industrial processes, as industries, governments, and scientists look for means to minimize their carbon footprint, enhance waste management, and reduce reliance on non-renewable resources. Through the integration of green chemistry principles into industrial processes, green synthesis is paving the way towards a greener future, promoting the creation of technologies that are conducive to environmental health without compromising industrial advancement and economic development [13].

There are several methods to synthesis nanomaterials, which are classified into three approaches like top-down approach, bottom-up approach and green synthesis method. Figure 1 illustrates classification of various synthesis methods.

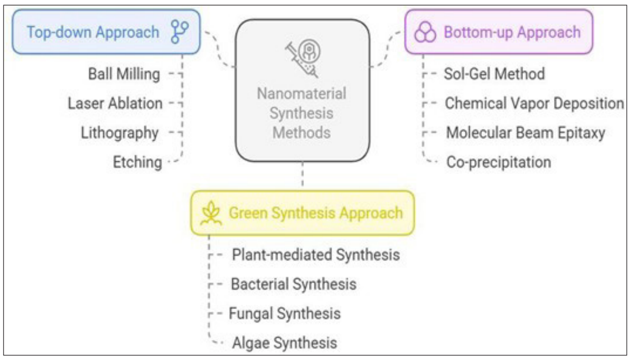

Figure 1: Classification of synthesis methods for NPs.

Drawbacks of synthesis using conventional methods

High energy consumption: Conventional methods such as ball milling, chemical vapor deposition (CVD), and sol-gel processes often require high temperatures, pressures, and prolonged reaction times. These conditions lead to significant energy consumption, making the synthesis process expensive and environmentally unsustainable. For example, CVD requires temperatures above 800 °C, which is energy-intensive and not feasible for large-scale production.

Use of toxic chemicals: Many conventional methods rely on toxic chemicals, solvents, and reducing agents. For instance, chemical reduction methods often use sodium borohydride ($NaBH_4$) or hydrazine (N_2H_4), which are hazardous to human health and the environment. These chemicals can contaminate water sources and pose risks to laboratory workers.

Poor control over size and shape: Conventional methods often lack precision in controlling the size, shape and morphology of NPs. For example, in chemical precipitation, the rapid mixing of reactants can lead to uneven particle sizes. This inconsistency affects the NPs' optical, electrical, and catalytic properties, fritting their application in sensitive fields like medicine and electronics.

Aggregation and stability issues: NPs synthesized using conventional methods often aggregate due to their high surface energy. This aggregation reduces their surface area-to-volume ratio, diminishing their effectiveness in applications like catalysis and drug delivery. Stabilizing agents such as surfactants or polymers are often required, which can complicate the synthesis process and introduce impurities.

Low yield and scalability issues: Many conventional methods, such as laser ablation and are discharge, have low yields and are difficult to scale up for industrial production. For example, laser ablation produces a limited number of NPs per batch, making it unsuitable for large-scale manufacturing. This limitation hinders the commercialization of NP-based products.

Environmental pollution: Conventional synthesis methods often involve non-renewable resources and generate harmful by-products. For instance, the sol-gel process produces large amounts of organic waste, while chemical reduction methods release toxic gases. These practices contradict the principles of green chemistry and contribute to environmental degradation.

High cost of equipment and maintenance: Conventional methods require expensive equipment and specialized facilities. For example, CVD and laser ablation systems are costly to install and maintain. Additionally, further increasing the overall cost of NP synthesis.

Limited biocompatibility: NPs synthesized using conventional methods may not be biocompatible, limiting their use in biomedical applications. For example, residual toxic chemicals from chemical reduction methods can cause adverse effects in biological systems, such as inflammation or cytotoxicity. This issue is particularly critical in drug delivery and diagnostic applications. Limitation of conventional methods is summarized in table 1.

In the fields of food science, nutrition, and packaging, nanotechnology has become a game-changing instrument that provides creative solutions to pressing problems pertaining to food safety, quality control, preservation, and environmental sustainability [14, 15]. The use of MONPs, such as zinc oxide (ZnO), titanium dioxide (TiO_2), copper oxide (CuO), silver (Ag), and cerium oxide (CeO_2), in these technologies is interest of the researchers [16, 17]. As these NPs have shown, improving the functional characteristics of food packaging systems. It has been demonstrated that adding these NPs to packaging materials increases their mechanical strength, barrier effectiveness, and antimicrobial properties [18, 19]. This increases food product shelf life and guarantees higher safety standards. The creation of sustainable packaging substitutes for traditional plastics is further advanced by the combination of MONPs with biodegradable and bio-based polymers like chitosan and nanocellulose [20, 21]. At the same time, real-time food quality and microbiological contamination monitoring is made possible by the integration of MONP-based nanosensors into intelligent packaging systems, which advances active and smart packaging technologies [22]. The development of functional meals with additional health benefits is supported by the targeted distribution and improved bioavailability of nutrients and bioactive chemicals made possible by nano-encapsulation techniques [23]. The broad use of nanotechnology in the food industry is hampered by a number of issues, notwithstanding the notable developments. The necessity for thorough safety assessments is highlighted by worries about the possible migration of NPs into food matrices, their long-term toxicological effects, environmental persistence, and interactions within the human gastrointestinal system [24]. In addition, there are still unanswered questions about consumer acceptance, regulatory ambiguities, and the viability of large-scale, ecologically friendly synthesis techniques, especially in low- and middle-income nations. Therefore, even if nanotechnology has a lot of potential to transform food systems, its effective integration may require a well-rounded strategy that encourages creativity while guaranteeing strict safety evaluation, legal compliance, environmental stewardship, and moral accountability [25, 26]. Some of the metal and MONPs mentioned in table 2 which are useful for food sectors.

The use of nanotechnology in agriculture signifies a paradigm change in the direction of resilient, accurate, and sustainable food production systems. In order to address agricultural challenges through improved nutrient delivery, stress mitigation, and environmental remediation, the reviewed studies emphasize the diverse roles of metal and MONPs, including Ag, CuO, ZnO, iron oxide, and TiO_2 [27, 28]. The application of nanofertilizers, which increase nutrient-use efficiency and reduce environmental losses, is one of the most extensively researched topics. By allowing for the gradual and focused release of nutrients to plants, these materials lessen runoff, volatilization, and leaching. According to studies, when plants are nutrient-deficient, nano-formulated nutrients work better than conventional fertilizers by boosting absorption and fostering plant vigor [29, 30].

In terms of biotic stress management, metal-based NPs like AgNPs and CuONPs have strong antibacterial and pesticidal characteristics that disrupt plant pathogens' cellular ma-

Table 1: Summarization of limitations of conventional methods.

S no.	Drawbacks	Description	Example
1	High energy consumption	Conventional methods require high temperature, pressures and long reaction times, thus leading to high energy usage	CVD (requires temperature > 800 °C)
2	Use of toxic chemicals	Many methods use harmful chemicals that pose risks to human health and environment	$NaBH_4$ in chemical reduction methods
3	Poor control over size and shape	Lack of precision in controlling NPs properties affects their performance in sensitive applications	Chemical precipitation (rapid mixing causes uneven particle sizes)
4	Aggregation and stability issues	High surface energy leads to aggregation, reducing the effectiveness of NPs	NPs in catalytic or drug delivery systems (aggregation reduces performance)
5	Low yield and scalability	Some methods have low yields and are difficult to scale for industrial production	Laser ablation (limited NPs per batch)
6	Environmental pollution	Conventional methods often generate harmful waste and emissions that harm the environment	Sol-gel process (organic waste production)
7	High cost of equipment and maintenance	Expensive equipment and specialized facilities are required, which are rising costs	CVD and laser ablation (high equipment costs)
8	Limited biocompatibility	NPs made by conventional methods may be toxic or cause adverse biological effects	Residual chemicals causing inflammation

Table 2: Materials (NPs) studied in different food areas.

Paper title	Focus area	Materials studied	Applications	Advantages	Challenges
Recent innovations in metal-based NPs for food packaging	Safety and environmental impact of MONPs in food packaging	Ag, Cu, ZnO, TiO_2	Active, intelligent packaging	Strong antimicrobial, gas barrier, ultraviolet protection	Toxicity, environmental impact, regulatory gaps
Advancements in MO bio-nanocomposites for sustainable food packaging	MO bio-nanocomposites for food packaging	ZnO, TiO_2, CuO, Ag, carbon nanotubes (CNTs)	Antimicrobial packaging, improved mechanical/barrier properties	Enhanced shelf life, eco-friendly, biodegradable	Migration, scalability, cost
Enhancement in food packaging via metal nanomaterials	Innovations and future of active packaging	Ag, ZnO, CuO, TiO_2	Mechanical, thermal, antimicrobial, barrier	Shelf life, safety, smart packaging	Regulations, toxicity, cost, scale-up
Synthesis and applications of ZnO, CuO, CeO_2 NPs	Synthesis and applications of MONPs	ZnO, CuO, CeO_2	Agriculture, pharma, food packaging	Biocompatibility, green synthesis methods	Toxic chemical methods, reproducibility
MO-nanocellulose composites	Intelligent and active packaging using nanocellulose	ZnO, TiO_2 + nano-cellulose	Shelf-life extension, smart indicators	Mechanical strength, biodegradability	NP migration, regulatory issues
Metallic and MOs NPs for pathogen sensing	Nanosensors for food safety	Au, Ag, ZnO, CuO	Detection of Escherichia coli, *Salmonella*	High sensitivity, quick response	Integration into packaging, cost
Role of nanotechnology in food processing	Nanotech in food preservation	Various MONPs, nanocapsules	Food safety, shelf-life, packaging	Antimicrobial, antioxidant	Public perception, cost, toxicity
Nanoencapsulation of food ingredients	Encapsulation of nutrients using nanotech	Liposomes, MONPs	Delivery of nutrients, fortification	Improved bioavailability, stability	Nutrient interaction, food compatibility
Dominance of MOs in nanotech	General applications of MONPs	TiO_2, Vanadium dioxide (VO_2)	Photocatalysis, smart packaging, sensors	Stability, reactivity, photoactive	Limited to TiO_2 and VO_2 focus

chinery. Rajpal et al. [31] found that such NPs not only lower pest populations but also boost plant immune responses by inducing reactive oxygen species (ROS) and activating stress-related genes [31]. Furthermore, nanosensors integrated into crop systems enable real-time detection of diseases and nutritional deficits, hence promoting precision agriculture methods [31, 32]. Another important area of research is the potential of nanomaterials for cleanup. Heavy metals, agrochemicals, and organic contaminants can be effectively removed from soil and water systems using materials like graphene oxide, charcoal, zero-valent iron (nZVI), and nano-clays. Through adsorption, redox processes, and catalysis, these nanomaterials interact with pollutants; in certain investigations, they have achieved removal efficiencies of over 90%. This has significant ramifications for lowering pollution in the environment caused by excessive use of fertilizer and pesticides [30, 33].

The literature also notes a number of ecological and toxicological issues in spite of these advantages. Overuse or poorly designed NP applications can harm soil microbiota, prevent seed germination, and cause oxidative stress in plants. According to Xu et al. [34], for example, MONPs increase rice yield and stress tolerance, but if used excessively, they can also result in oxidative damage and hormonal abnormalities. Similarly, Rastogi et al. [35] pointed out that by generating ROS and inhibiting enzymes, NPs could disrupt photosynthesis and respiration in plants. Many elements, including particle size, coating, soil pH, organic matter, and ambient variables, affect the behavior and destiny of NPs in agroecosystems. Chen [36] stated the importance of knowing how these parameters affect NP transport, bioavailability, and accumulation in plant tissues and soils. In table 3, tabulated different areas of application where NPs can be more useful in agriculture.

Green synthesis techniques that use biological templates like plant extracts, which lower toxicity and increase biocompatibility, are being used as part of efforts to increase safety and scalability. These practices are becoming more popular in both rich and developing nations, and they are consistent with the ideas of sustainable agriculture. Last but not least, two major obstacles to the broad use of agricultural goods offered by nanotechnology are regulatory and public knowledge gaps. The evaluation of the long-term ecological implications of NP use is complicated by the existing absence of field-level safety studies and defined risk assessment methodologies [37, 38].

Green synthesis

Green synthesis of NPs is a new, eco-friendly approach based on natural materials like plants, microbes, and biopolymers for synthesizing NPs. When compared with conventional chemical processes, which are generally derived from toxic reagents and produce harmful waste, green synthesis is a green chemistry-guided eco-friendly route. Plants contain reducing, stabilizing, and capping agents, and are potential candidates for synthesizing an enormous range of NPs like metal, MO, and hybrid nanoparticles. Besides reducing the ecological footprint, the green approach is also distinguished by unique advantages like low cost and biocompatibility. In this article, we introduce the different plant-mediated approaches for NP synthesis and their possible applications from medicine to environmental cleaning.

Table 3: NPs used in various agricultural sectors.

Area of application	NPs used	Key benefits	Risks/Challenges	Recommendations
Nano-fertilizers	ZnO, Fe_2O_3, TiO_2, CuO, nZVI	Enhanced nutrient use efficiency-controlled release-reduced leaching	Phytotoxicity at high dose-environmental accumulation	Optimize dosage and use green synthesis techniques
Pest and disease control	AgNPs, CuO, ZnO, TiO_2	Antimicrobial action-pest repellent-pathogen suppression	Resistance development-soil microbial imbalance	Field validation and safe delivery mechanisms
Nanopesticides	Ag, Cu, Zn, silica-based nanomaterials	Enhanced pesticide efficiency-reduced chemical use	Non-target effects-bioaccumulation	Regulate application levels and toxicity profiles
Nanosensors	AuNPs, ZnO, QDs, CNTs	Real-time stress/pathogen detection-precision farming support	High cost-sensor degradation	Encourage integration with internet of things and smart farming systems
Seed priming and germination	Fe_2O_3, CuO, ZnO, TiO_2	Faster germination-uniform seedling growth	Hormonal disruption-ROS toxicity	Use low-concentration bio-compatible coatings
Soil remediation	nZVI, nano-clays, graphene oxide, biochar	Heavy metal removal-organic pollutant degradation	Long-term fate in soil is unclear	Use biodegradable nanomaterials; monitor persistence
Biotic stress management	Metal and MONPs (Fe, Cu, Zn, Ag)	ROS induction-stress-related gene activation	Oxidative damage to plant tissues	Use in stress-tolerant crop breeding programs

Plant based green synthesis

Plant mediated green synthesis of NPs is increasingly gaining momentum as it is cost-effective, easy, and environmentally friendly. Unlike traditional synthesis involving toxic chemicals and excessive energy, plant mediated synthesis uses plant extract rich to convert metal salts (gold (Au) chloride, Ag nitrate) into NPs and prevent aggregation [39]. The process starts with the pre-treatment of a plant extract, which is blended with a solution of a metal salt to trigger the reduction of metal ions. It is a room-temperature process and hence energy-conservation. The most striking advantage is the environmental friendliness, as it substitutes toxic chemicals with non-toxic plant material, thus minimizing environmental impact. Additionally, it is cost-saving as plant material is easily accessible and cheap [40]. The plant-mediated route offers a high level of control over the size, shape, and surface features of the NPs, which is critical for applications in medicine, such as drug delivery and imaging. The thus prepared NPs have extensive applications in medicine, environmental clean-up, and agriculture. AgNPs, for example, are sure to be antimicrobial in nature, which makes them crucial for wound healing, and AuNPs are investigated for drug delivery and diagnostic imaging [41, 42].

In the environmental sector, plant-synthesized NPs help in water purification and pollutant degradation, while in agriculture, they are used as bio-pesticides and growth stimulants [43]. Desai et al. [44] reported copper ferrite ($CuFe_2O_4$) NPs synthesis using *Pongamia pinnata* plant leaves and suggested that the copper nano ferrites can be used as catalyst for oxidative decarboxylation of phenyl acetic acid derivatives [44]. Chandrani et al. [45] synthesized cobalt ferrite nano NP ginger root extract and performed phenol red dye degradation (Figure 2 shows schematic diagram of photo catalytic mechanism) which is suggested cobalt ferrite nano particles are good photo catalyst [45]. Nabi et al. [46] synthesized lemon peel extracted TiO_2 NP and studied their photo catalytic activity. Some MOs are synthesized using different plant extracts and their applications are tabulated in table 4.

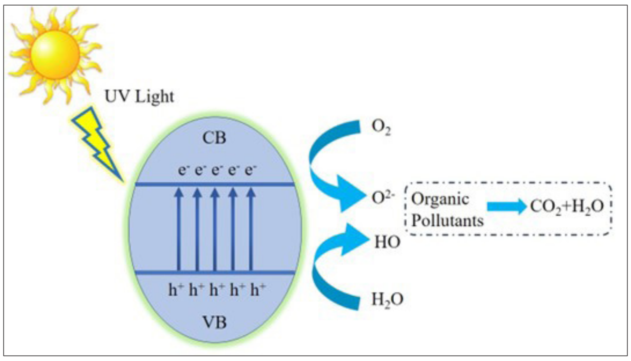

Figure 2: Mechanism of photocatalytic activity.

Bacterial based green synthesis

Bacterial synthesis of NPs is a new and very promising green chemistry method that provides a sustainable, environmentally friendly, and cost-effective pathway for NP synthesis. In contrast to traditional methods using toxic reagents, high temperatures, and energy-costly processes, bacterial synthesis employs microorganisms to reduce metal ions and produce NPs under mild conditions. The process leverages the intrinsic metabolic processes of bacteria, thus being not only environmentally friendly but also scalable to industrial processes. Bacterial synthesis is especially useful in that it eliminates the use of toxic reagents, minimizes the requirement for high energy inputs, and produces NPs that are biocompatible, thus very suitable for medical and environmental applications [58].

Bacterial NPs are synthesized by intracellular and extracellular processes. In intracellular synthesis, metal ions are brought inside the bacterial cell, where intracellular compounds and enzymes reduce them to produce NPs inside the cell. Intracellular synthesis has been carried out successfully in bacteria such as *Pseudomonas stutzer*, *Escherichia coli*, and *Bacillus cereus*, which have been shown to store nanoparticles in their cell structures. Extracellular synthesis is achieved through secretion of enzymes or metabolites by bacteria outside into the external environment, where metal ion reduction

Table 4: Examples of plant-based green synthesis.

S no.	Plant	NP	Size (nm)	Shape	Applications	Ref.
1	*Pongamia pinnata*	$CuFe_2O_4$	36 nm	Non uniform	Catalytic activity	[44]
2	Ginger root and cardamom seeds	$CoFe_2O_4$	14 - 20 nm	Porous and sponge like form	Photo catalytic activity and dye degradation	[45]
3	Lemon peel	TiO_2	80 - 140 nm	Spherical	Water cleaning, self-surface cleaning and energy production	[46]
4	Ginger root and cardamom seeds	$MnFe_2O_4$	40 - 50 nm	Non uniform	Dye degradation and antimicrobial activity	[47]
5	Lemon extract	$ZnFe_2O_4$	50 - 60 nm	Spherical	Photo catalysis and hyperthermia	[48]
6	Acanthe phylum bracteatum	Ag	29 - 68 nm	Spherical	Antibacterial and antimicrobial properties	[49]
7	Croton sparsiflorus	Au	12 - 13 nm	Spherical, triangular and rod	Antibacterial and anticancer	[50]
8	*Tinospora cordifolia*	Cu	-	Spherical	Catalytic degradation	[51]
9	*Clostridium acetobutylicum*	Fe	59 - 61 nm	Porous, sponge like form	Hydrogenase activity	[52]
10	Plantain peel	Fe_3O_4	50 nm	Spherical	Water filter, biomedical field and drug delivery	[53]
11	Banana peel	Pd	50 nm	Spherical	Devising sensors and in making active membranes	[54]
12	Black cumin seed	Pt	1 - 6 nm	Spherical	Bacterial pathogens	[55]
13	*Albizia lebbeck*	ZnO	66 nm	Irregular spherical	Antimicrobial, antioxidant and cytotoxic activity	[56]
14	*Jatropha curcas* L.	ZnS	10 nm	Spherical	Electronics and biomedical	[57]

and nanoparticle formation take place outside the bacterial cells. Extracellular synthesis offers a more convenient recovery and purification method of nanoparticles as the particles are formed in the medium and can be easily recovered [59].

Bacterial NP synthesis can be utilized to synthesize nanoparticles of a range of materials, including Au, Ag, copper, and selenium. These NPs are used for a range of applications in various areas. For instance, Ag NPs produced by bacteria have been reported to be antimicrobial and are thus promising agents for novel antibacterial therapies, especially wound healing and coatings of medical devices. In the environment, bacteria-synthesized NPs have been discovered to be effective in the treatment of wastewater because they can be utilized for the removal of heavy metals, dyes, and other pollutants. Moreover, NPs can be used in bioremediation procedures, whereby bacteria are utilized for the breakdown of toxic substances in the environment. In agriculture, bacteria-synthesized NPs are being studied for their capability to enhance plan growth act as bio-pesticides and protect plants from a range of pathogens [60]. Examples of bacterial based synthesis are shown in table 5.

Advantages of bacterial NP synthesis are the ability to control the size, shape, and surface properties of the NPs, which are of utmost relevance to specific applications. Also, bacteria can be engineered genetically to produce NPs with specific surface properties, i.e., the surface area of NPs can be enhanced, and they become useful in drug delivery systems, biosensors, and environmental clean-up. With further studies, bacterial NP synthesis holds great promise for a wide variety of industrial, biomedical, and environmental applications and provides a cleaner approach than conventional methods of NP synthesis [61].

Fungal based green synthesis

Fungal NP synthesis represents a fast-evolving, highly promising green chemistry process with a sustainable, environmentally benign, and cost-efficient method of nanomaterial preparation. In contrast to otherwise toxic chemical reagents, high temperatures, and energy-hungry protocols needed for traditional methods, fungal synthesis employs microorganisms to chemically reduce metal ions and deposit NPs under mild, ambient conditions. The process employs the fungal metabolic machinery itself, thus combining eco-friendliness with process scalability for industrially viable applications. Fungal synthesis is especially appealing since it circumvents the use of toxic reagents, minimizes the requirement for large-scale energy inputs, and yields NPs with biocompatibility, which imparts to them unique appropriateness for biomedicine as well as ecological purposes [66].

The fungal NPs synthesis process occurs through both intracellular and extracellular mechanisms. In intracellu-

Table 5: Examples of bacterial based green synthesis.

S no.	Bacteria	NP	Size (nm)	Shape	Application	Ref.
1	*B. cereus*	Ag	5 nm	Spherical	Catalysis, data storage and microelectronics	[62]
2	*E. coli*	Au	20 nm	Spherical	Direct electrochemistry of Hb	[63]
3	*Lactobacillus* sp	$BaTiO_3$	20 - 80 nm	Spherical	Drug delivery and Bioelectronics	[64]
4	*P. stutzer*	Cu	50 - 150 nm	Cubic	Medicine and antimicrobial	[65]

lar synthesis, metal ions are transported into the fungal cell, where they are reduced by enzymes and other compounds to form NPs within the cell. This approach has been successfully demonstrated in fungi such as *Verticillium* species and *Neurospora crassa*, which have been shown to accumulate NPs inside their cellular structures. On the other hand, extracellular synthesis is the method through which fungi release enzymes or metabolites into the external medium, where metal ion reduction and NP synthesis occur outside the fungal cells. The method is simpler for the recovery and purification of NPs since the particles are synthesized in the medium and can be recovered with ease. Fungi such as *Fusarium oxysporum*, *Aspergillus niger*, and *Penicillium* sp. have been employed to synthesize NPs extracellularly [67].

Fungal production of NPs can yield variety of NPs such as Au, Ag, copper, and selenium. NPs produced have usage in a variety of industries. AgNPs derived from fungi, for example, are renowned for their antimicrobial properties and are potential agents for novel antibacterial therapy, particularly for wound treatment and medical device coating. In the environmental sector, NPs from fungi have been found to hold promise as agents for wastewater treatment because they are able to be used to desorb heavy metals, dyes, and other contaminants. Further, these nanoparticles can be employed in bioremediation whereby fungi are used to break down toxic chemicals in the environment. In agriculture, NPs produced by fungi are under investigation to be utilized in enhancing plant growth, as bio-pesticides, and as protection for plants against a variety of pathogens. Fungi can also be genetically modified to produce NPs of desired properties, such as greater surface area, to be highly efficient in drug delivery systems, biosensors, and environmental purification. Fungi based synthesized NPs and its application tabulated in table 6. As research in this direction continues to rise, fungal NP synthesis promises to be invaluable for a vast array of industrial, medical, and environmental applications, providing an eco-friendly route to the conventional synthesis of NPs [67].

Algae based green synthesis

Algae-mediated NP synthesis a green and eco-friendly process that exploits the high bioactive content of algae to reduce metal ions in NPs. It is an environment-friendly and green process in contrast to the conventional chemical and physical processes that employ toxic reagents and high energy input. Algae, microalgae, and macro algae are suitable sources of secondary metabolites such as polyphenols, proteins, polysaccharides, and terpenoids, which are used as reducing and stabilizing agents in NP synthesis [70].

The synthesis is initiated with the isolation of suitable algal species with high bioactive compound contents. The optimum growth conditions of the selected algae are utilized to produce maximum biomass. Harvested algal biomass is purified from impurities and then exposed to extraction procedures to yield an aqueous extract rich in bioactive molecules. The aqueous extract is used as the capping and reducing agent in the NP synthesis process. Algae extracted nano synthesized shown in table 7.

In conventional synthesis process, the metal salt solution is combined with the algal extract, for example, Ag nitrate ($AgNO_3$) for AgNPs or chloroauric acid ($HAuCl_4$)) for AuNPs. The reaction mixture is incubated under controlled conditions, such as temperature, pH, and illumination, in order to facilitate the reduction of metal ions by the bioactive compounds present in the algal extract. Appearance of NPs is commonly marked by color change in solution, for example, dark pink color change from yellow marks formation of AuNPs. The duration of reaction may range from few minutes to many hours, with the concentration of metal salt, algal extract -composition, and incubation condition [70].

Following synthesis, the NPs are usually purified by centrifugation to eliminate any remaining biomass or unreacted metal ions. The purified NPs are subsequently analyzed using a range of analytical methods to establish their size, shape, crystalline structure, and surface properties. Typical characterization techniques are spectroscopy, which tracks the surface plasmon resonance of the NPs; transmission microscopy, which gives high-resolution images of the morphology of the NPs; and X-ray diffraction, which determines the crystalline phases present in the NPs [71].

This alga mediated synthesis method not only reduces environmental footprint through the avoidance of toxic chemicals but is also beneficial in terms of scalability and NP property tailoring through the use of different algal species or adjusting reaction parameters. The biogenic NPs formed by this method have been promising in a range of applications, such as antimicrobial agents, drug delivery, environmental clean-up and catalysts in chemical reactions.

Table 6: Examples of fungi based green synthesis.

S no.	Fungi	NP	Size (nm)	Shape	Application	Ref.
1	*Phoma glomerata*	Ag	60 - 80 nm	Spherical	Drug delivery	[67]
2	*Verticillium luteoalbum*	Au	10 nm	Spherical	Drug delivery	[68]
3	*Aspergillus flavus*	TiO_2	62-74 nm	Spherical	Antibacterial activity	[69]

Table 7: Examples of algae based green synthesis.

S. no.	Algae	NP	Size (nm)	Shape	Application	Ref.
1	*Caulerpa racemosa*	Ag	5 - 25 nm	Spherical, triangular	Antibacterial activity	[72]
2	*Sargassum wightii*	Au	8 - 12 nm	Planar	Drug delivery	[73]
3	HSMV-1	Fe_3O_4	50 - 70 nm	Bullet-shaped	Magnetic navigation	[74]

Challenges in green synthesis

Green synthesis, the strategy to formulate environmentally friendly and sustainable means to synthesize chemicals, materials, and pharmaceuticals, is a possible method that can serve as an alternative to traditional synthesis techniques. But owing to some of the technical, economic, and regulatory challenges, green synthesis has been experiencing challenges in its large-scale utilization and deployment. These technical, economic, and regulatory challenges hinder the extensive use of green synthesis to fully reap its global advantage.

One of the most significant issues is scalability of the green synthesis process. While many green methods, for example, solvent use of water or renewable raw material use, are at laboratory scale, scaling up such processes to industrial production is often found to be High energy requirements, yield inconsistency, and access to renewable raw materials can make large-scale application economically unfeasible. For example, renewable feedstock like plant material can be inconsistent in quality and availability and hence make standardization of production processes difficult [75]. Further, the economic viability of green technology development and deployment can be a massive bottleneck, especially for industries founded on established, low-cost conventional processes.

The second most relevant issue is the creation of efficient and stable green catalysts for green synthesis. Catalysts are necessary in order to minimize energy consumption and waste generation in chemical reactions. Although nanomaterials, biocatalysts, and other green catalysts are very promising, they are generally deficient in the desired selectivity, stability, and reusability in industrial processes [76]. For example, bio catalytic enzymes are susceptible to destruction under harsh conditions of reactions and are limited in their application. Similarly, fabrication of nanomaterial catalysts involves the use of toxic precursors at times in contradiction to the principles of green chemistry. Rectifying these issues calls for revolutionary advancements in catalyst design and engineering.

Regulatory and standardization problems are also a significant impediment to the adoption of green synthesis. Currently, there is no unified regulatory regime or standard set of metrics to quantify the “greenness” of a process. Without guidelines, industries may not invest in green technologies because they may be unsure of the like hood of compliance as well as the risk [77]. Also, the absence of universally accepted parameters for determining sustainability makes comparing and optimizing eco-friendly synthesis protocols more difficult. Resolving these issues requires collaboration between policymakers, scientists and industrial stakeholders to develop effective standards and incentives for greenery.

Conclusion

A revolutionary development in materials science, the green synthesis of NPs brings nanotechnology into line with environmental stewardship and sustainability ideals. In contrast to traditional techniques, which frequently use dangerous chemicals and energy-intensive procedures, green synthesis uses biological systems, such as plants, bacteria, fungi, and algae, to create metal and MONPs in a way that is both environmentally responsible and commercially feasible. The shape, biocompatibility, and functional performance of NPs can be better controlled by these biologically mediated routes. Green-synthesized nanomaterials have shown great importance in agriculture for nutrient delivery, stress resistance, and environmental remediation; in food science, they help with smart packaging and safety sensing; and in medicine, they allow for less toxic targeted therapies and diagnostics. But as the field develops, issues including environmental permanence, public acceptance, regulatory frameworks, and NP toxicity continue to be significant obstacles. The strong interdisciplinary cooperation, standardized risk assessment procedures, and open policy development may be necessary to meet these difficulties. Green synthesis is at the vanguard of nanotechnology's next chapter, providing not just scientific innovation but also a model for responsible technological advancement as global priorities change towards low-impact technologies and circular economies.

Acknowledgements

None.

Conflict of Interest

None.

References

1. Kharissova OV, Kharisov BI, González OC, Méndez YP, Israel L. 2019. Greener synthesis of chemical compounds and materials. *Roy Soc Open Sci* 6(11): 1-41. https://doi.org/10.1098/rsos.191378
2. Olaniyan OF, Ariwaodo CA, Ibrahim SO, Atolani O, Kambizi L. 2025. Advances in green synthesis and application of nanoparticles from crop residues: a comprehensive review. *Sci Afr* 28: e02654. https://doi.org/10.1016/j.sciaf.2025.e02654
3. Wang D, Saleh NB, Sun W, Park CM, Shen C, et al. 2019. Next-generation multifunctional carbon–metal nanohybrids for energy and environmental applications. *Environ Sci Technol* 53(13): 7265-7287. https://doi.org/10.1021/acs.est.9b01453
4. Ganesh KN, Deqing Z, Miller SJ, Rossen K, Chirik PJ, et al. 2021. Green chemistry: a framework for a sustainable future. *Environ Sci Technol* 55(13): 8459-8463. https://doi.org/10.1021/acs.est.1c03762
5. Ying S, Guan Z, Ofoegbu PC, Clubb P, Rico C, et al. 2022. Green synthesis of nanoparticles: current developments and limitations. *Environ Technol Innov* 26: 102336. https://doi.org/10.1016/j.eti.2022.102336
6. Sheldon RA. 2012. Fundamentals of green chemistry: efficiency in reaction design. *Chem Soc Rev* 41(4): 1437-1451. http://dx.doi.org/10.1039/C1CS15219J
7. Subramaniyam V, Subashchandrabose SR, Thavamani P, Megharaj M, Chen Z, et al. 2015. *Chlorococcum* sp. MM11—a novel phyco-nanofactory for the synthesis of iron nanoparticles. *J Appl Phycol* 27: 1861–1869. https://doi.org/10.1007/s10811-014-0492-2
8. Ameta, SK, Rai AK, Hiran D, Ameta R, Ameta SC. 2020. Use of Nanomaterials in Food Science. In Ghorbanpour M, Bhargava P, Varma A, Choudhary D (eds) Biogenic Nano-Particles and their Use in Agro-ecosystems. Springer, Singapore, pp 457–488.
9. Mishra M, Sharma M, Dubey R, Kumari P, Ranjan V, et al. 2021. Green synthesis interventions of pharmaceutical industries for sustainable development. *Curr Res Green Sustain Chem* 4: 100174. https://doi.org/10.1016/j.crgsc.2021.100174
10. Tang Y, Zhao W, Zhu G, Tan Z, Huang L, et al. 2024. Nano-pesticides and fertilizers: solutions for global food security. *Nanomaterials* 14(1): 90. https://doi.org/10.3390/nano14010090

11. Hamad AF, Han JH, Kim BC, Rather IA. 2018. The intertwine of nanotechnology with the food industry. *Saudi J Biol Sci* 25(1): 27-30. https://doi.org/10.1016/j.sjbs.2017.09.004
12. Singh T, Shukla S, Kumar P, Wahla V, Bajpai VK, et al. 2017. Application of nanotechnology in food science: perception and overview. *Front Microbiol* 8: 1-7. https://doi.org/10.3389/fmicb.2017.01501
13. Gałuszka A, Migaszewski Z, Namieśnik J. 2013. The 12 principles of green analytical chemistry and the SIGNIFICANCE mnemonic of green analytical practices. *Trends Anal Chem* 50: 78-84. https://doi.org/10.1016/j.trac.2013.04.010
14. Rai DP, Sahoo AK, Shrivastav OP, Charmode N, Prasad S, et al. 2022. A review on aspects of nanotechnology in food science and animal nutrition. *ES Food Agrofor* 8: 12-46.
15. Nandhini J, Bellarmin M, Prakash SS, Sowmya SD, Karthikeyan E. 2024. Advancements in metal oxide bio-nanocomposites for sustainable food packaging: fabrication, applications, and future prospectives. *Food Bioeng* 3: 438–463. https://doi.org/10.1002/fbe2.12106
16. Abass AM, Abdoon FM. 2024. Synthesis, characterization, and applications of metal oxides of ZnO, CuO, and CeO_2 nanoparticles: a review. *J Appl Organomet Chem* 4(4): 349-366. https://doi.org/10.48309/jaoc.2024.471305.1220
17. Nirmal N, Vashisht P, Sharma S, Singh L, Awasti N, et al. 2024. Enhancement in the active food packaging system through metal-based nanomaterials: a review of innovations, challenges, and future directions. *Discov Food* 4: 1-20. https://doi.org/10.1007/s44187-024-00189-2
18. Ahari H, Jafari A, Ozdal T, Moradi S, Bahari HR, et al. 2025. Recent innovations in metal-based nanoparticles for food packaging: a focus on safety and environmental impact. *Appl Food Res* 5(1): 100860. https://doi.org/10.1016/j.afres.2025.100860
19. Stuparu-Cretu M, Braniste G, Necula GA, Stanciu S, Stoica D, et al. 2023. Metal oxide nanoparticles in food packaging and their influence on human health. *Foods* 12(9): 1882. https://doi.org/10.3390/foods12091882
20. Perera KY, Pradhan D, Rafferty A, Jaiswal AK, Jaiswal S. 2023. A comprehensive review on metal oxide-nanocellulose composites in sustainable active and intelligent food packaging. *Food Chem Adv* 3: 100436. https://doi.org/10.1016/j.focha.2023.100436
21. Joshi NC, Negi PB, Gururani P. 2024. A review on metal/metal oxide nanoparticles in food processing and packaging. *Food Sci Biotechnol* 33(6): 1307–1322. https://doi.org/10.1007/s10068-023-01500-0
22. Ungureanu C, Tihan GT, Zgârian RG, Fierascu I, Baroi AM, et al. 2022. Metallic and metal oxides nanoparticles for sensing food pathogens—an overview of recent findings and future prospects. *Materials* 15(15): 5374. https://doi.org/10.3390/ma15155374
23. Shah MA, Mir SA, Bashir M. 2017. Nanoencapsulation of Food Ingredients. In Nayak B, Nanda A, Bhat M (eds) Integrating Biologically-Inspired Nanotechnology into Medical Practice. IGI Global Scientific Publishing, pp 132-152.
24. Kulkarni AS, Ghugre PS, Udipi SA. 2016. 15 - Applications of Nanotechnology in Nutrition: Potential and Safety Issues. In Grumezescu AM (ed) In Nanotechnology in the Agri-Food Industry. Novel Approaches of Nanotechnology in Food. Academic Press, pp 509-554.
25. Sahoo M, Panigrahi C, Vishwakarma S, Kumar J. 2022. A review on nanotechnology: applications in food industry, future opportunities, challenges and potential risks. *J Nanotechnol Nanomaterials* 3(1): 28-33. https://doi.org/10.33696/Nanotechnol.3.029
26. Fanzo J, Rudie C, Sigman I, Grinspoon S, Benton TG, et al. 2022. Sustainable food systems and nutrition in the 21st century: a report from the 22nd Annual Harvard Nutrition Obesity Symposium. *American J Clin Nutr* 115(1): 18-33. https://doi.org/10.1093/ajcn/nqab315
27. Maity D, Gupta U, Saha S. 2022. Biosynthesized metal oxide nanoparticles for sustainable agriculture: next-generation nanotechnology for crop production, protection and management. *Nanoscale* 14(38): 13950-13989. https://doi.org/10.1039/d2nr03944c
28. Hyder S, Ul-Nisa M, Shahzadi, Shahid H, Gohar F, et al. 2023. Recent trends and perspectives in the application of metal and metal oxide nanomaterials for sustainable agriculture. *Plant Physiol Bioch* 202: 107960. https://doi.org/10.1016/j.plaphy.2023.107960
29. Kaningini AG, Nelwamondo AM, Azizi S, Maaza M, Mohale KC. 2022. Metal nanoparticles in agriculture: a review of possible use. *Coatings* 12(10): 1586. https://doi.org/10.3390/coatings12101586
30. Nabam A, Aravinda T, Ghanghas R, Menjo K, Mohapatra R, et al. 2025. A review on nanotechnology in soil science: recent advances in soil remediation, fertilization and carbon sequestration. *Asian J Crop Soil Plan Nutri* 11(2): 15–34. https://doi.org/10.9734/ajsspn/2025/v11i2507
31. Rajpal VR, Dhingra Y, Khungar L, Mehta S, Minkina T, et al. 2024. Exploring metal and metal-oxide nanoparticles for nanosensing and biotic stress management in plant systems. *Curr Res Biotechnol* 7: 100219. https://doi.org/10.1016/j.crbiot.2024.100219
32. Abobatta W. 2021. Role of nano-biotechnology in agricultural sector. *Adv Res Organic Inorganic Chem* 2: 1-4. https://doi.org/10.54026/AROIC/1004
33. Ochoa LG, Balderrama Carmona AP. 2022. Use of nanotechnology for the removal of agrochemicals from soil and water. *J Biomed Res Environ Sci* 3(10): 1185-1188. https://doi.org/10.37871/jbres1576
34. Xu M, Zhang Q, Lin X, Shang Y, Cui X, et al. 2023. Potential effects of metal oxides on agricultural production of rice: a mini review. *Plants* 12(4): 778. https://doi.org/10.3390/plants12040778
35. Rastogi A, Zivcak M, Sytar O, Kalaji H M, He X, et al. 2017. Impact of metal and metal oxide nanoparticles on plant: a critical review. *Front Chem* 5: 1-16. https://doi.org/10.3389/fchem.2017.00078
36. Chen H. 2018. Metal based nanoparticles in agricultural system: behavior, transport, and interaction with plants. *Chem Speciat Bioavailab* 30(1): 123-134. https://doi.org/10.1080/09542299.2018.1520050
37. Hamad HT, Al-Sharify ZT, Al-Najjar SZ, Gadooa ZA. 2020. A review on nanotechnology and its applications on fluid flow in agriculture and water resources. *IOP Conf Ser Mater Sci Eng* 870(1): 1-13. https://doi.org/10.1088/1757-899X/870/1/012038
38. Panakkal H, Gupta I, Bhagat R, Ingle AP. 2021. Effects of Different Metal Oxide Nanoparticles on Plant Growth. In Ingle AP (ed) Nanotechnology in Plant Growth Promotion and Protection. John Wiley & Sons Ltd.
39. Iravani S, Korbekandi H, Mirmohammadi SV, Zolfaghari B. 2014. Synthesis of silver nanoparticles: chemical, physical and biological methods. *Res Pharm Sci* 9(6): 385-406.
40. Jadoun S, Rizwan A, Jangid N, Meena R. 2021. Green synthesis of nanoparticles using plant extracts: a review. *Environ Chem Lett* 19: 355–374. https://doi.org/10.1007/s10311-020-01074-x
41. Vanlalveni C, Lallianrawna S, Biswas A, Manickam S, Changmai B, et al. 2021. Green synthesis of silver nanoparticles using plant extracts and their antimicrobial activities: a review of recent literature. *RSC Adv* 11(5): 2804–2837. http://dx.doi.org/10.1039/D0RA09941D
42. Mehra V, Kumar S, Tamang AM, Chandraker S. 2025. Green synthesis of gold nanoparticles (AuNPs) by using plant extract and their biological application: a review. *BioNanoSci* 15(1): 18. https://doi.org/10.1007/s12668-024-01703-7
43. Pirsaheb M, Gholami T, Seifi H, Dawi EA, Said EA, et al. 2024. Green synthesis of nanomaterials by using plant extracts as reducing and capping agents. *Environ Sci Pollut Res* 31(17): 24768–24787. https://doi.org/10.1007/s11356-024-32983-x
44. Desai HB, Jani K, Gohel B, Chandrani DN, Patel B, et al. 2025. Copper nanoferrites produced by extracting the leaves of the *Pongamia pinnata* plant and their catalytic reaction in oxidative decarboxylation process. *Inorg Chem Commun* 174(1): 113922. https://doi.org/10.1016/j.inoche.2025.113922

45. Chandrani DN, Ghosh S, Tanna AR. 2024. Green synthesis for fabrication of cobalt ferrite nanoparticles with photocatalytic dye degrading potential as a sustainable effluent treatment strategy. *J Inorg Organomet Polym* 34: 3100–3114. https://doi.org/10.1007/s10904-023-02981-6

46. Nabi G, Ain QU, Tahir MB, Nadeem RK, Iqbal T, et al. 2020. Green synthesis of TiO2 nanoparticles using lemon peel extract: their optical and photocatalytic properties. *Int J Environ Anal Chem* 102(2): 434–442. https://doi.org/10.1080/03067319.2020.1722816

47. Chaudhari A, Kaida T, Desai HB, Ghosh S, Bhatt RP, et al. 2022. Dye degradation and antimicrobial applications of manganese ferrite nanoparticles synthesized by plant extracts. *Chem Phys Impact* 5: 100098. https://doi.org/10.1016/j.chphi.2022.100098

48. Jogi JK, Singhal SK, Jangir R, Dwivedi A, Tanna AR, et al. 2022. Investigation of the structural and optical properties of zinc ferrite nanoparticles synthesized via a green route. *J Electron Mater* 51(10): 5482–5491. https://doi.org/10.1007/s11664-022-09813-2

49. Mehrdad F, Khalil F. 2010. Biological and green synthesis of silver nanoparticles. *Turkish J Eng Env Sci* 34: 281-287.

50. Boomi P, Poorani GP, Selvam S, Palanisamy S, Jegatheeswaran S, et al. 2020. Green biosynthesis of gold nanoparticles using *Croton sparsiflorus* leaves extract and evaluation of UV protection, antibacterial and anticancer applications. *Appl Organomet Chem* 34(5): e5574. https://doi.org/10.1002/aoc.5574

51. Sharma P, Pant S, Poonia P, Kumari S, Dave V, et al. 2018. Green synthesis of colloidal copper nanoparticles capped with *Tinospora cordifolia* and its application in catalytic degradation in textile dye: an ecologically sound approach. *J Inorg Organomet Polym* 28(6): 2463–2472. https://doi.org/10.1007/s10904-018-0933-5

52. Mohanraj S, Kodhaiyolii S, Rengasamy M, Pugalenthi V. 2014. Green synthesized iron oxide nanoparticles effect on fermentative hydrogen production by *Clostridium acetobutylicum*. *Appl Biochem Biotechnol* 173(1): 318–331. https://doi.org/10.1007/s12010-014-0843-0

53. Venkateswarlu S, Rao YS, Balaji T, Prathima B, Jyothi NVV. 2013. Biogenic synthesis of Fe_3O_4 magnetic nanoparticles using plantain peel extract. *Mater Lett* 100: 241-244. https://doi.org/10.1016/j.matlet.2013.03.018

54. Bankar A, Joshi B, Ravi Kumar A, Zinjarde S. 2010. Banana peel extract mediated novel route for the synthesis of palladium nanoparticles. *Mater Lett* 64(18): 1951-1953. https://doi.org/10.1016/j.matlet.2010.06.021

55. Aygun A, Gülbagca F, Ozer LY, Ustaoglu B, Altunoglu YC, et al. 2020. Biogenic platinum nanoparticles using black cumin seed and their potential usage as antimicrobial and anticancer agent. *J Pharm Biomed Anal* 179: 112961. https://doi.org/10.1016/j.jpba.2019.112961

56. Ghulam N. 2020. Green synthesis of TiO_2 nanoparticles using lemon peel extract: their optical and photocatalytic properties. *J Environ Anal Chem* 102(2): 434–442. https://doi.org/10.1080/03067319.2020.1722816

57. Umar H, Kavaz D, Rizaner N. 2018. Biosynthesis of zinc oxide nanoparticles using *Albizia lebbeck* stem bark, and evaluation of its antimicrobial, antioxidant, and cytotoxic activities on human breast cancer cell lines. *Int J Nanomedicine* 14: 87-100. https://doi.org/10.2147/IJN.S186888

58. Hudlikar M, Joglekar S, Dhaygude M, Kodam K. 2012. Latex-mediated synthesis of ZnS nanoparticles: green synthesis approach. *J Nanoparticle Res* 14(5): 865. https://doi.org/10.1007/s11051-012-0865-x

59. Ghosh S, Ahmad R, Zeyaullah M, Khare SK. 2021. Microbial nano-factories: synthesis and biomedical applications. *Front Chem* 9: 1-19. https://doi.org/10.3389/fchem.2021.626834

60. Lucía CA, Athanasios S, Pavlo M, Dirk L. 2023. Insights into the bacterial synthesis of metal nanoparticles. *Front Nanotechnol* 5: 1-20. https://doi.org/10.3389/fnano.2023.1216921

61. Lahiri D, Nag M, Sheikh HI, Sarkar T, Edinur HA, et al. 2021. Microbiologically-synthesized nanoparticles and their role in silencing the biofilm signaling cascade. *Front Microbiol* 12: 1-19. https://doi.org/10.3389/fmicb.2021.636588

62. Jadoun S, Chauhan NPS, Zarrintaj P, Barani M, Varma RS, et al. 2019. Synthesis of nanoparticles using microorganisms and their applications: a review. *Environ Chem Lett* 20(5): 3153–3197. https://doi.org/10.1007/s10311-022-01444-7

63. Ganesh BMM, Paramasamy G. 2009. Production and structural characterization of crystalline silver nanoparticles from *Bacillus cereus* isolate. *Colloids Surf B Biointerfaces* 74(1): 191-195. https://doi.org/10.1016/j.colsurfb.2009.07.016

64. Du L, Jiang H, Liu X, Wang E. 2007. Biosynthesis of gold nanoparticles assisted by *Escherichia coli* DH5α and its application on direct electrochemistry of hemoglobin. *Electrochem Commun* 9(5): 1165-1170. https://doi.org/10.1016/j.elecom.2007.01.007

65. Jha AK, Prasad K. 2010. Ferroelectric $BaTiO_3$ nanoparticles: biosynthesis and characterization. *Colloids Surf B Biointerfaces* 75(1): 330-334. https://doi.org/10.1016/j.colsurfb.2009.09.005

66. Varshney R, Bhadauria S, Gaur MS, Pasricha R. 2011. Copper nanoparticles synthesis from electroplating industry effluent. *Nano Biomed Eng* 3(2): 115-119.

67. Guilger-Casagrande M, de Lima R. 2019. Synthesis of silver nanoparticles mediated by fungi: a review. *Front Bioeng Biotechnol* 7: 1-16. https://doi.org/10.3389/fbioe.2019.00287

68. Birla SS, Tiwari VV, Gade AK, Ingle AP, Yadav AP, et al. 2009. Fabrication of silver nanoparticles by *Phoma glomerata* and its combined effect against *Escherichia coli*, *Pseudomonas aeruginosa* and *Staphylococcus aureus*. *Lett Appl Microbiol* 48(2): 173-179. https://doi.org/10.1111/j.1472-765X.2008.02510.x

69. Gericke M, Pinches A. 2006. Microbial production of gold nanoparticles. *Gold Bull* 39: 22–28. https://doi.org/10.1007/BF03215529

70. Rajakumar G, Rahuman AA, Roopan SM, Khanna VG, Elango G, et al. 2012. Fungus-mediated biosynthesis and characterization of TiO_2 nanoparticles and their activity against pathogenic bacteria. *Spectrochim Acta A Mol Biomol Spectrosc* 91: 23-29. https://doi.org/10.1016/j.saa.2012.01.011

71. Chaudhary R, Nawaz K, Khan AK, Hano C, Abbasi BH, et al. 2020. An overview of the algae-mediated biosynthesis of nanoparticles and their biomedical applications. *Biomolecules* 10(11): 1498. https://doi.org/10.3390/biom10111498

72. Shera SS, Banik RM. 2021. Algal Nanoparticles: Synthesis and Characterization. In Thangadurai D, Sangeetha J, Prasad R (eds) Bioprospecting Algae for Nanosized Materials. Nanotechnology in the Life Sciences. Springer, Cham, pp 25-69.

73. Kathiraven T, Sundaramanickam A, Shanmugam N, Balasubramanian T. 2014. Green synthesis of silver nanoparticles using marine algae *Caulerpa racemosa* and their antibacterial activity against some human pathogens. *Appl Nanosci* 5(4): 499–504. https://doi.org/10.1007/s13204-014-0341-2

74. Singaravelu G, Arockiamary JS, Kumar VG, Govindaraju K. 2007. A novel extracellular synthesis of monodisperse gold nanoparticles using marine alga, *Sargassum wightii* Greville. *Colloids Surf B Biointerfaces* 57(1): 97-101. https://doi.org/10.1016/j.colsurfb.2007.01.010

75. Lefèvre CT, Abreu F, Schmidt ML, Lins U, Frankel RB, et al. 2010. Moderately thermophilic magnetotactic bacteria from hot springs in Nevada. *Appl Environ Microbiol* 76(11): 3740-3743. https://doi.org/10.1128/AEM.03018-09

76. Warner JC. 2010. Green Chemistry: A Necessary Step to a Sustainable Future. International Seminar on Nuclear War and Planetary Emergencies-42nd Session.

77. Clark JH, Duncan JM. 2007. Handbook of Green Chemistry and Technology. John Wiley & Sons.