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Review articles

ADVANCES IN THE GREEN SYNTHESIS OF PLANT-BASED NANOPARTICLES AND THEIR DIVERSE APPLICATIONS

Salsabila Qonita Zhafira[1], Brilian Nabila[1], Putri Amilia[1], Rhodiatul Eka Savira Putri[1], Herdhanti Shang Maharani[1], Didit Dwi Siswantoro[1], Md Monir Hossain[2], Elma Sakinatus Sajidah[1*]

[1]Department of Biology, Faculty of Mathematics and Natural Science, Universitas Negeri Surabaya-60231, Surabaya, East Java, Indonesia
[2]School of Science, RMIT University, Melbourne, Australia
*Correspondence: elmasajidah@unesa.ac.id

ABSTRACT
Plant-based nanoparticle synthesis has emerged as a sustainable and promising alternative to conventional methods due to its simplicity, environmental friendliness, and improved biocompatibility. This article discusses the latest advancements in the green synthesis of various types of nanoparticles using plant extracts, with a focus on their applications in biomedical, environmental, and agricultural fields. Key phytochemicals such as flavonoids, alkaloids, terpenoids, and phenolics play a crucial role in the reduction and stabilization of nanoparticles. Silver nanoparticles (AgNPs) are the most synthesized type, known for their strong antimicrobial and anticancer activities. Inorganic nanoparticles exhibit high stability and potential in targeted therapy and pollutant degradation, while organic and carbon-based nanoparticles offer flexibility in drug delivery and diagnostic innovations. The use of plants such as *Lawsonia inermis*, *Aloe vera*, and *Curcuma longa* in nanoparticle synthesis has proven effective against pathogens and cancer cells with minimal toxicity. The integration of nanotechnology and phytochemistry opens new avenues in addressing global challenges in health, agriculture, and environmental conservation.
Keywords: Nanoparticles; green synthesis; phytochemicals; biomedical application; environmental fields

INTRODUCTION.

Nanoparticles are one of the therapeutic agents consisting of nanoparticles to control the biodistribution or reduce the toxicity of drugs or biologics. In addition, nanotechnology combines various fields of science such as engineering, chemistry, physics, biology, and medicine, with the main goal of building objects on an atomic scale. One nanometer, which is one billionth of a meter, is equivalent to the diameter of a hydrogen atom. Nanoparticles are also nanomaterials measuring between 1 to 100 nanometers so this size allows nanoparticles to exhibit unique physical and chemical properties compared to conventional materials (1).

Research on nanoparticles has grown rapidly in many fields, including nanomedicine, nanobiotechnology, and the environment. Such as research (2) which has been done by Sarkar et al. 2024 where nanoparticles are used to overcome biological problems in drug delivery, but also to target cancer stem cells. Studies have also been conducted on the uptake of nanoparticles by cells, which is a key step in understanding nano-bio interactions and biomedical applications. The synthesis of nanoparticles can be done through various methods, including mechanical, chemical, and biological. Conventional methods such as chemical reduction, although effective, often involve the use of toxic chemicals and energy-intensive processes (3). As one of the alternative methods green synthesis is emerging as a more sustainable approach. Green synthesis offers several significant advantages, including being environmentally friendly, cost-effective, non-toxic, and simple in execution. The process does not require high-pressure, high-temperature conditions or complex equipment, making it an attractive and justifiable option. In addition, green synthesis often results in nanoparticles that are more biocompatible and less toxic (4). One of the main approaches in green synthesis is the use of plant-based extracts. Plant extracts are rich in phytochemical compounds such as flavonoids, terpenoids, alkaloids, polyphenols, and vitamins, which serve as natural reducing and stabilizing agents. Examples of plants that have been used in the green synthesis of nanoparticles include *Ocimum sanctum* (tulsi), *Curcuma longa* (turmeric), and *Azadirachta indica* (neem) (5).

Previous research on plant-based nanoparticles has shown great potential in various applications such as that conducted by Anju et al. (6). Using the synthesis of silver nanoparticles (AgNPs) using *Aloe vera* leaf inner gel extract, the results showed that the visible color change and plasmon peak at 400 nm in the UV-Visible spectrum confirmed the successful formation of AgNPs so that it can be confirmed that the functional groups in asemmanan act as crucial reducing and stabilizing agents, helping the formation and maintaining the stability of AgNPs. Enhanced antimicrobial activity against various Gram-positive bacteria such as *Staphylococcus aureus* and Gram-negative bacteria such as *Escherichia coli*. In addition, research on plant-based was also conducted by Serag et al. (7). This research focuses on the development of folic acid carbon dot nanocomposites as a strategy to overcome the limitations of Curcumin in cancer treatment, such as low stability, poor water solubility, and limited absorption. By utilizing the highly biocompatible carbon dot as a carrier, this study begins with the synthesis of carbon dot using folic acid as raw material through hydrothermal method (7).

Due to these advantages gathering information related to plant-based nanoparticles is essential. Such advantages, including environmental friendliness, biocompatibility, and effectiveness in various applications, demonstrate the great potential of plant-based nanoparticles to significantly impact future nanoparticle-related research. The first section is dedicated to ONP production methods. The second section presents techniques for characterization of some physical, chemical, and biological properties of ONPs that are important for food applications. The third section discusses the potential applications of ONPs to improve the quality, storage stability, sensory, and bioactivity of foods.

HISTORY OF NANOPARTICLES

Nanotechnology combines various fields of science such as engineering, chemistry, physics, biology, and medicine, with the main goal of building objects on an atomic scale. One nanometer, which is one billionth of a meter, is equivalent to the diameter of a hydrogen atom. The terms “nanotechnology” or “nanotech” used today refer to the ability to control and manipulate matter at the nanoscale. Through chemical, molecular and supramolecular methods, scientists can create nanoparticles, nanomaterials and materials with nanostructures. The field also examines the special characteristics that arise due to changes in particle size, especially when the size is reduced to the nanoscale (8). Nonetheless there is a widespread theoretical foundation of modern nanotechnology believed to have originated with Richard Feynman in 1959's “There's Plenty of Room at the Bottom”, which posited that the idea of manipulating matter on an atomic scale (9). It is suspected that nanoparticles and nanostructured materials have been formed from meteorites originating from the Big Bang process, the initial creation of the universe and Earth. Nanodiamonds found in meteorites are believed to be one of the most common types of pre-solar grains found (10). Natural nanomaterials are believed to have played an important role in the evolution of life on Earth, from the existence of the first cells to the emergence of humans (9). Since prehistoric times, humans have been interacting with and utilizing nanomaterials and their derivatives, albeit unknowingly. Smoke and soot from ancient fires, containing nanoparticles such as fullerenes and graphene, were used in cave paintings in locations such as Sulawesi, Indonesia, around 40,000 BC. This shows the early utilization of nanomaterials in art. Rapid developments in nanomaterial characterization technology have enabled a deeper understanding of their properties (11).

In ancient civilizations, the use of nanomaterials became more deliberate. In ancient Egypt, oil lamp soot was used for black pigments, and natural clay minerals were utilized as early as 5000 BC. Around 2575 BC, "Egyptian blue", a synthetic pigment based on glass and nano-sized quartz, was produced. The ancient Mayan civilization (8th century BC) also created "Mayan blue", a composite of indigo dye with highly stable nanoporous clay. The production of the first metallic nanoparticles, such as copper nanoparticles in red glass in Italy (1200-1000 BC) and silver-gold in [th]e Roman Lycurgus Cup, shows early knowledge of nano-optical properties. Lustre ceramics in Islamic and European countries (9th to 17th centuries) utilized Ag and Cu nanoparticles for optical effects, a technique also applied to Japanese Satsuma glass and medieval church windows. "Damascus" steel (13th-18th centuries) even contained cementite nanocables and carbon nanotubes. The contemporary period in the development of nanomaterials lasted until 1959 and modern nanotechnology began in 1960 (12).
The modern era of nanotechnology began with systematic research. In the mid-1850s, Michael Faraday investigated a colloidal suspension of "Ruby" gold, showing how gold nanoparticles changed the color of the solution. The development of electron microscopy (Ernest Ruska and Max Knoll, 1935) and scanning tunneling microscopy (Gerd Binning and Heinrich Rohrer) became key breakthroughs that enabled the visualization and manipulation of nanomaterials at the atomic scale, paving the way for modern nanotechnology as we know it today (12). Significant evolution in nanotechnology, particularly in the context of drug delivery systems, became apparent from the mid-20th century. Modern drug delivery technology began around 1952 with the Spansule sustained-release capsule, and in 1989, Lupron Depot opened the era of injectables and long-term implants. Another important milestone was the advent of PEGylation in 1990 with Adagen, which significantly improved the systemic circulation of nanoparticles. In 1995, Doxil became the first FDA-approved nanomedicine, proving the clinical potential of nanoparticles (13). Various types of nanoparticles such as mesoporous silica nanoparticles (MSNs) and lipid nanoparticles (LNPs) for mRNA vaccines (14) continues to be developed, marking a shift from basic research to real clinical applications.

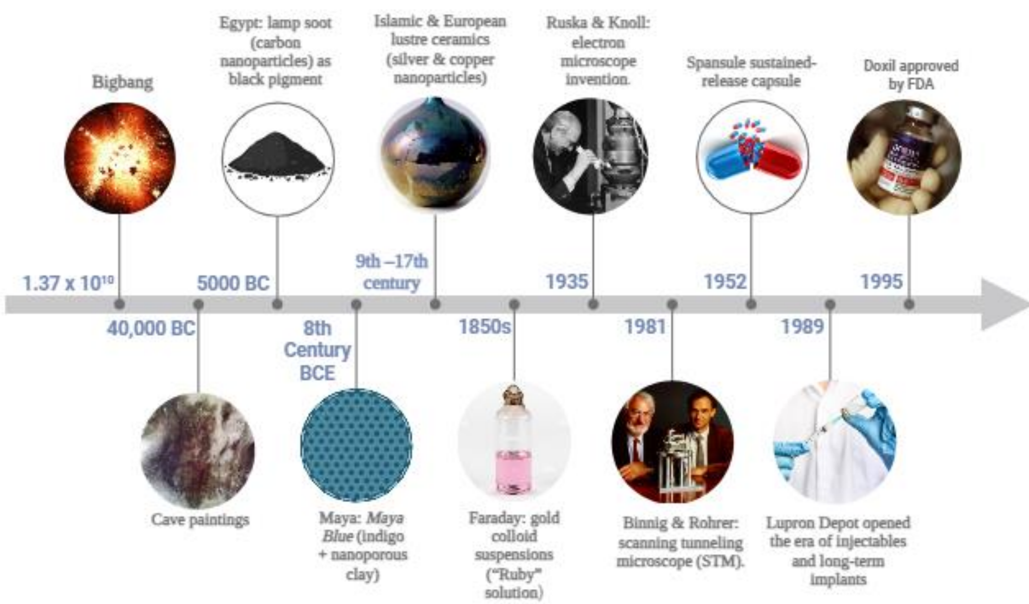

Figure 1. History of Nanoparticles from 40,000 BC to 1995.

TYPE OF NANOPARTICLES

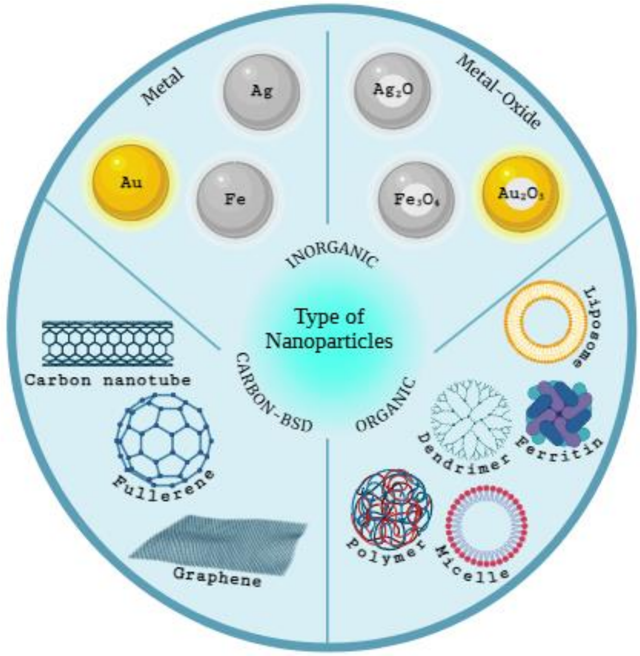

Figure 2. Schematic representation of the main types of NPs classified into organic, inorganic, and carbon-based NPs reproduce from (15)

Nanoparticles have recently been used across health, industry, cosmetics, and agriculture (16). They include polymeric, magnetic, liposomes, carbon nanotubes, quantum dots, dendrimers, and metallic types (17). Based on composition, they are classified as organic, inorganic, or carbon-based (18). The three major groups have advantages and disadvantages that can be compared through **Table 1**.

Organic Nanoparticles (ONPs)

Organic nanoparticles (ONPs) are synthesized from organic molecules with a size of 100 nm or less (19). Frequently used ONPs are dendrimers, liposomes, micelles, and protein complexes such as ferritin (20). These nanoparticles are made from organic compounds such as proteins, carbohydrates, lipids, and polymers. ONPs can be applied to the food field to guide the development of safe food products (21). In addition, ONPs are an advanced technology in the field of photodynamic therapy that can improve tumor selectivity and reduce photosensitivity to the skin (22).

ONPs have various properties such as being sensitive to temperature, electromagnetic radiation including heat and light, biodegradable, and non-toxic (23). ONPs are often formed through noncovalent intermolecular interactions making them more labile in nature and offering a route to exit the body (24). Such flexible structures can be designed using synthetic, natural or protein polymers (25). However, flexibility can allow nanoparticles to undergo shape or conformational changes in response to environmental stimuli so applications are needed to detect physicochemical changes, molecular binding interactions, and stimulus-driven effects (24). Other drawbacks of ONPs are low reproducibility and drug entrapment issues (26). In addition, some types of ONPs such as chitosan have another disadvantage, namely poor mechanical processing properties and insolubility in common organic solvents so they need to be combined with a large number of other polymeric or inorganic or organic substances (27).

Inorganic Nanoparticles (INPs)

Inorganic nanoparticles (INPs) are particles that are not made of carbon (28). It consist of metal and metal-oxide nanoparticles (29,30). While metal-oxide nanoparticles are metal nanoparticles that are oxidized in the presence of oxygen at room temperature, thereby increasing their reactivity compared to metal nanoparticles. For example, iron oxide (Fe_3O_4), titanium oxide (TiO_2), copper oxide (CuO), and zinc oxide (ZnO) (31). According to Bayda et al., the synthesis of INPs requires a relatively low cost (32) so it is more often used in various applications (33).

Various types of INPs can be used to improve the efficiency of photodynamic therapy in terms of vectorization, enhancement of photosensitizer loading, or theranostics (34). INPs possess outstanding properties such as high quantum yield and drug loading capacity, and can also function as drug carriers in photothermal (PTT) and photodynamic therapy (PDT) (35). According to Poon & Patel, INPs have disadvantages including low biocompatibility and lack of biodegradability (26) (36). In addition, INPs have reproducibility values that tend to be low (37). However, Fancher et al. revealed that several FDA-approved drugs, such as lercanidipine, felodipine, aliskiren, and superoxide dismutase, when loaded into INPs (metal) showed advantages in the form of biocompatibility, biodegradability, and low toxicity levels so that they can be potential candidates for further development as new agents in the treatment of resistant hypertension (38). Inorganic nanoparticles have robust crystalline lattices and hydrophilic properties, providing superior chemical and aqueous stability compared to organic nanoparticles (39,40).

Carbon-based Nanoparticles (CNPs)

Carbon-based nanoparticles (CNPs) are often utilized in biomedicine due to their unique chemical and physical properties including thermal, mechanical, electrical, optical, and structural diversity (41). These properties offer exceptional strength, flexibility, and electrical conductivity capabilities that are useful for various applications such as sensors, medical diagnosis, and treatment of a number of diseases (42). Carbon-based nanoparticles include graphene and its derivatives, carbon nanotubes, fullerenes, nanodiamonds, and other nanosized carbon allotropes (43). Different carbon nanoparticles, even those made from similar precursors, can show varying degrees of cytotoxicity. For example, carbonized polymer dots from different aromatic diamines exhibited different oxidative stress levels and cell viability impacts, indicating that nanoparticle structure and surface chemistry strongly influence biological responses (44).

Carbon-based nanoparticles (CNPs) have low solubility properties in aqueous and organic solvents, so their compatibility with polymer matrices can be hindered, which can reduce the utilization of their full potential (45). CNPs have low reproducibility (46). According to Morozova et al., the presence of humic substances or surfactants can either stabilize nanoparticles (by steric hindrance) or promote aggregation, depending on their concentration and type (47). One type of CNPs is graphene which has a very strong 2-D honeycomb structure and is widely used as a precursor for the synthesis of other CNPs (48). However, graphene has poor dispersion and aggregation in solution resulting in limitations in its use (49). In addition, CNPs fullerenes and carbon nanotubes are notably resistant to biodegradation (36).

Table 1. Characteristics of Each Type of Nanoparticle

Aspect	Carbon-Based Nanoparticles	Organic Nanoparticles	Inorganic Nanoparticles
Stability	Generally stable but can aggregate or degrade under some conditions (49, 47)	Less stable, sensitive to environmental conditions (23)	Highly stable under various conditions (39, 40)
Biocompability	Moderate; requires careful evaluation due to	High; often biodegradable and less toxic (23)	Generally good but depends on composition;

Aspect	Carbon-Based Nanoparticles	Organic Nanoparticles	Inorganic Nanoparticles
	toxicity risks (45, 44)		some toxicity concerns (26)
Biodegrability	Low (36)	High (23)	Low (36)
Reproducibility	Low (46)	Low (26)	Low (37)

Based on their internal characteristics, each type of nanoparticle has a tendency to be applied in certain fields. According to Anselmo & Mitragotri, organic nanoparticles (ONPs) have advantages over intravenously administered drugs, and inorganic nanoparticles (INPs) have many stimulus-responsive functions that are possible based on specific colloidal assemblies (50). Meanwhile, carbon-based nanoparticles (CNPs) are often utilized in the fields of energy storage, electronics, and sensors due to their outstanding thermal and electrical conductivity properties, exceeding normal materials such as silicon and metals (INPs) (49). Despite this trend, all three types of nanoparticles have the potential to be applied to all fields, as long as their beneficial properties and limitations are carefully considered.

All three types of nanoparticles share low reproducibility, posing challenges for large-scale homogeneity, though advances in technology are addressing this issue (51). However, technological advances are able to find solutions to these problems. Microfluidic systems have shown promising potential to modulate critical stages in nanosynthesis so that nanoparticle reproducibility is optimized with high yields (52). Reproducibility can also be improved through the selection of fast nanoparticle detection mechanisms such as surface-assisted laser desorption/ionization (SALDI) mass spectrometry (MS) due to the absence of an applied matrix (53).

Based on **Table 1.** it can be concluded that the selection of nanoparticle types whether ONPs, INPs, and CPNs is determined by their distinctive physical, chemical, and biological properties as they affect their level of effectiveness and safety in certain applications. According to Pugazhendhi et al., INPs are considered to have more potential in cancer treatment because they are more stable to high temperatures when compared to ONPs (54). INPs provide a higher advantage than ONPs in photodynamic therapy, as they can be activated by light without the need to release the photosensitizer (34). In addition, the cosmetic field more frequently uses INPs than ONPs due to their superior non-toxicity, hydrophilicity, biocompatibility, and stability (55). Thus, it can be seen that INPs are more frequently applied in various fields. This is not only due to the internal advantages of INPs themselves, but also influenced by external factors such as relatively cheaper production costs (32 ,33). In accordance with Hofmann-Amtenbrink et al.'s statement, external factors such as cost and development time are significant barriers to the utilization of nanoparticle technology (56).

PLANT BASED OF NANOPARTICLES

The preparation of nanoparticle materials can use environmentally friendly natural materials (green synthesis) as modifying or reducing agents, such as plants and microorganisms (bacteria and fungi). Reducing and stabilizing agents for plant-based nanoparticle synthesis are secondary metabolites and proteins, while microorganisms have key enzymes (57). When compared to conventional synthesis, green synthesis is proven to be superior in various aspects. Green synthesis allows for a 50% increase in production yield, 30% reduction in energy consumption, and up to 40% cost savings (58).

According to Paiva-Santos et al. plants are the starting materials that are more frequently used in nanoparticle synthesis (59). Plant-based nanoparticle synthesis can increase efficiency because microorganisms require a lot of effort and attention (60). In addition, plant-based synthesis does not require special reducing or capping agents or stabilizers (61). Various studies of synthesizing nanoparticles by utilizing plant bases were found, as shown on **Table 2.**

Table 2. Green Synthesis of Various Nanoparticles Using Plant Extracts

Plant Name	Type of Nanoparticle	Possible Biomolecules Involved in Reduction and Stabilisation	Particle size (nm)	Applications	References
Rhynchosia suaveolens	silver nanoparticles (AgNPs-F)	Polyphenolic compounds or flavonoids	10–30	Therapeutic application in cancer therapy	(62)
Aloe vera	silver nanoparticles (AgNPs)	Polysaccharides, flavanones, terpenoids	10-50	Antibacterial activity and antitumor.	(6, 57)
Carissa carandas	silver nanoparticles	Flavonoid, phenolic	28-60	Antioxidant, anticancer and antibacterial activities	(64)
Curcuma longa	Carbon dots (CDs)	Curcumin	6,8 (TEM)	Antibacterial and anticancer	(7)
Azadirachta indica	silver nanoparticles (Ag-NPs)	Flavonoids, polyphenols and limonoids	10-60 (TEM)	Anticancer, antibacterial and antioxidant	(59, 60)
Camellia sinensis	silver nanoparticles (Ag-NPs)	Flavonoids, amino acids, carboxylate, and carbonyl	14.9 (TEM)	Antibacterial, anticancer, and antidiabetic	(61, 62)
Moringa oleifera	silver nanoparticles (Ag-NPs)	Phenols, proteins, flavonoids, polysaccharides, and terpenoids.	50–60 (TEM)	Antimicrobial (antibacterial & antifungal) and Cytotoxicity	(69)
Teucrium polium	Silver nanoparticles (AgNPs)	Diterpenoids, flavonoids, iridoids, sterols, and terpenoids	70-100 (SEM)	Antitumor and cancer therapeutics	(70)
Zingiber officinale	nickel nanoparticles	Alkaloids, flavonoids,	35–45 nm (SEM)	Antibacterial, anti-leishmanial activity,	(71)

	(Ni-NPs)	zingiberene		antidiabetic and antioxidant activity	
Acai berry and Elderberry	Gold nanoparticles (AuNPs)	Flavonoids, polyphenols and anthocyanin.	1-100	For treatment of both the prostate and pancreatic cancers	(72)
Salvia miltiorrhiza	Silver nanoparticles (AgNPs)	Phenolic compounds, flavonoids, polyphenols	100 (TEM)	Anticancer potential in human prostate cancer LNCaP cell lines	(73)
Mukia maderaspatna	Gold and silver nanoparticles	Flavonoids, carotenoids, tannins	20–50 (TEM)	Cancer therapeutic activity	(74)
Curcumin	Polyamidoamine dendrimer (G0.5)	Diferuloylmetha-ne	100 (TEM)	anti-inflammatory, antioxidant, and anticancer activities)	(75)
Solanum lycopersicum	*Carbon dots* (CDs)	Phenolic acids, flavonoids and tannins	1-10 (TEM)	Antioxidant, antitumor	(76)
Ocimum canum	Silver Nanoparticles (AgNPs)	Flavonoids, terpenoids, phenolic compounds, proteins	40-95 (SEM)	Antibacterial activity	(77)
Peppermint	Nanoemulsion	Phenolic compounds, phenylpropanoid	Below to the 100	Herbal fungicides for controlling *Alternaria solani*	(78)
Terminalia chebula	Silver Nanoparticles (AgNPs)	Anthocyanine, coumarines, flavonoids, glycosides, phenols, quinones,	80-110 (SEM)	Antibacterial, antioxidant, and anticancer activity	(79)

		tannins, terpenoids, steroids, saponins			
Emblica officinalis	Selenium Nanoparticles (SeNPs) specifically phytofabricated selenium nanoparticles (PF-SeNPs)	Phenolics, flavonoids, tannins	15-40 (TEM)	Antioxidant activity, antimicrobial (antibacterial & antifungal) activity, biocompatibility, cytotoxicity	(80)
Catharanthus roseus	Silver Nanoparticles (AgNPs)	Hydroxyl groups, carbonyl and amide groups	2-15 (TEM)	Antibacterial activity	(81)
Syzygium cumini L.	Silver Nanoparticles (AgNPs)	Phenolics, flavonoids, sugars, ascorbic acid, proteins, and amino acids	15 (TEM) 30-40 (SEM)	Antioxidant activity	(82)
Psidium guajava	Silver Nanoparticles (AgNPs)	Phenolics, flavonoids, terpenoids, tannins, alkenes, aromatic rings	55 (TEM)	Antibacterial activity	(83)
Tridax procumbens	Silver Nanoparticles (AgNPs)	Peptides, terpenoids, polyphenol, alkaloids, fosinopril, phenols, amines, fluoro-compounds	11.1 - 45.4 (TEM)	Antimicrobial (antibacterial & antifungal) activity and anticancer activity	(84)
Punica granatum	Silica Nanoparticles (SiNPs)	Phenolics, alkaloids, terpenoids, proteins	12 (SEM)	Antibacterial activity	(85)

Allium sativum	Silver Nanoparticles (AgNPs)	Organosulfur compounds (allicin, alixin, diallyl sulfide, diallyl disulfides), sulfur amino acids, alkaloids, diterpenes, saponins, carbohydrates and lipids	40-60 (SEM)	Antibacterial activity, antifungal activity, anti-inflammatory and anti-tumor properties	(86)
Lawsonia inermis	Silver Nanoparticles (AgNPs)	Lawsone gallic acid	10-50 (TEM)	Antibacterial, antifungal, anti-inflammatory, anticancer, and antioxidant activity	(87)
Clerodendrum inerme	Silver Nanoparticles (AgNPs)	Carbon-based compounds, sulfur, silicon	30-90 (SEM)	Antioxidant activity and antimicrobial: antibacterial activity	(88)
Cinnamomum zeylanicum	Silver Nanoparticles (AgNPs)	Aldehyde carbonyl group, alkane,aromatic acid ester, phenolic compound, benzene ring	53-66 (SEM)	Antibacterial activity, antifungal activity, and antileishmanial efficacy	(89)
Acer oblongifolium	Silver Nanoparticle (AgNP)	Alkanes, alkynes, amines, aromatic compounds	3-8 (SEM)	Antibacterial, antiproliferative/ anticancer, antioxidant	(90)
Moringa oleifera	INPs (FeNP)	Amino acids, alkaloids, flavonoids, and phenolic compounds	3,4-7,4 (HRTEM)	Water decontamination (nitrate remover and antibacterial activity against *E. coli*)	(91)

Citrus sinensis	ONPs (Nano-fibrillated cellulose) and INP (AgNP)	Cellulose and flavonoid	44–50 and 15–16 (TEM)	Heavy metal (cadmium and chromium) absorben	(92)
Cynometra ramiflora	INPs (magnetic iron oxide nanoparticles (MIONPs))	Alkaloids, phenolic compounds, saponins, and steroids	58,5 (SEM)	Degradation of pollutant dye (methylene blue)	(93)
Brassica oleracea var. Botrytis	INPs (AgNPs)	Polyphenols	35.08	Degradation of pollutant dye (methylene blue)	(94)
Cissus quadrangular-is (L.)	Oxide nanoparticles (IONPs)	Gallic acid derivatives, steroids, flavonoids, stilbenes, and triterpenes	113.8 (SEM)	Pesticidal plant, antioxidant, antiinflammato-ry, and anticancer agents.	(95)
Pongamia glabra (Vent.)	Silver nano liquid (AgNLs)	Glycosidic compounds and phytochemicals	29 (SEM)	Pesticidal plants, antioxidant, and antifungal activity.	(96)

Based on **Table 2.**, by synthesizing nanoparticles using extracts from plant parts, nanoparticles play an important role in various fields, such as pharmacology, which has the ability to target treatment to specific cells and can increase the effectiveness of treatment or therapy in the field of pharmacology, the environment, and agriculture.

Pharmacological Field

Nanoparticles can be used in the health sector and can be synthesized from *Annona muricata* (62), *Aloe vera* (6, 57), *Carissa carandas* (64), *Curcuma longa* (7), *Azadirachta indica* (59, 60), *Camellia sinensis* (61, 62), *Moringa oleifera* (69), *Teucrium polium* (70), *Zingiber officinale* (71), Acai berry and Elderberry (72), *Salvia miltiorrhiza* (73), *Mukia maderaspatna* (74), *Cissus quadrangularis* (L.) (95), *Pongamia glabra* (Vent.) (96), *Curcumin* (75), *Solanum lycopersicum* (76), *Ocimum canum* (77), Peppermint (78), *Terminalia chebula* (79), *Emblica officinalis* (80), *Catharanthus roseus* (81), *Syzygium cumini* L. (82), *Psidium guajava* (83), *Tridax procumbens* (84), *Punica granatum* (85), *Allium sativum* (86), *Lawsonia inermis* (87), *Clerodendrum inerme* (88), *Cinnamomum zeylanicum* (89), *Acer oblongifolium* (90).

Based on **Table 2.**, plant-based nanoparticles synthesized for healthcare applications generally use silver nanoparticles (AgNPs). In recent days, silver nanoparticles (AgNPs) have become the most promising nanomaterial for biological applications, particularly as a new antimicrobial agent (97). Silver nanoparticles (AgNPs) are highly sought after for biomedical applications due to their remarkable antimicrobial activity. However, traditional synthesis methods (chemical and physical) raise health concerns due to toxicity, high production costs, and energy consumption. As an alternative, biological methods that utilize microorganisms and natural products offer economical and biocompatible AgNP synthesis. Plant extract-based synthesis stands out as a safe, cost-effective, and environmentally friendly approach, producing biocompatible AgNPs with enhanced properties. AgNPs synthesized from plants have the potential to be used as antimicrobial, anticancer, anti-inflammatory, and drug delivery agents in various biomedical applications, making them an innovation that can address the limitations of traditional methods in the biomedical sector (98). One example is the green synthesis and comprehensive characterization of silver nanoparticles using *Lawsonia inermis* extract for biological applications in Nithya et al. research (87), the results show that green AgNP synthesized from *Lawsonia inermis* is biocompatible and exhibits multifunctional biomedical potential as an antimicrobial, antioxidant, anti-inflammatory, and anticancer agent. The nanoparticles exhibited strong antibacterial activity against *Escherichia coli, Klebsiella pneumoniae, Salmonella typhi,* and *Staphylococcus aureus*, with zones of inhibition reaching up to 23 mm. Additionally, they showed potent antifungal effects against *Aspergillus niger, Aspergillus flavus, Fusarium,* and *Penicillium species*. In anticancer assays, the AgNPs displayed cytotoxic activity against A549 lung cancer cells with an IC_{50} value of 50 µg/mL. Antioxidant analysis revealed hydrogen peroxide scavenging up to 71% at a concentration of 50 µg/mL, while anti-inflammatory testing showed inhibition of protein denaturation with an IC_{50} of 6 mg/mL, which is comparable to standard diclofenac (2 mg/mL).

Nanoparticles in the field of health, as shown in **Table 2.** are commonly used in antibacterial and anticancer applications. Nanoparticles, particularly those based on metals, have garnered significant attention in biomedical applications, especially for antibacterial and anticancer purposes. Zinc oxide nanoparticles (ZnO NPs) have emerged as promising candidates due to their biocompatibility, low toxicity, and ability to induce the production of reactive oxygen species and cell apoptosis (99). Similarly, iron oxide nanoparticles (Fe_3O_4 NPs) have shown potential in cancer detection, targeted drug delivery, and antibacterial applications (100). The antibacterial properties of metals and metal oxide nanoparticles are being extensively studied as alternatives to antibiotics, addressing growing concerns about antibiotic resistance. These nanoparticles exhibit various mechanisms of action against bacteria, which are influenced by factors such as bacterial strain, biofilm formation, and the physicochemical properties of the nanoparticles (101).

Nanoparticles exert antibacterial activity through several interrelated mechanisms. One of the main mechanisms is the production of reactive oxygen species (ROS) such as hydroxyl radicals, which damage important biomolecules such as DNA, proteins, and lipids, especially in small nanoparticles with high surface areas. Additionally, metallic nanoparticles like AgNP release metal ions (Ag^+) that penetrate bacterial cell membranes and interact with sulfhydryl groups on proteins, disrupting enzyme function and protein structure. Nanoparticles can also directly damage important biomolecules, including DNA and proteins, and inhibit ribosomal function and protein synthesis. Another mechanism involves reduced ATP production by inactivating important enzymes and ribosomal subunits. Furthermore, direct interaction of nanoparticles with cell walls and membranes causes structural damage, particularly in Gram-negative bacteria, which have thinner cell walls and a negative charge, thereby increasing ion uptake and intracellular damage (102).

Meanwhile, in anticancer applications, nanoparticles target cancer cells specifically, delivering drugs more effectively while reducing side effects (103). There are various methods for formulating nanoparticles, including nanoprecipitation, extraction/evaporation, and emulsification. Magnetic

nanoparticles, in particular, have shown anticancer activity by inducing apoptosis in cancer cells (104). The integration of nanoparticles with biosensors has improved the sensitivity of cancer biomarker detection, potentially improving early diagnosis and patient survival rates. Nanoparticles can also target the microenvironment of tumors and specific organelles in cancer cells (103).
Nanoparticles have shown promising applications in the biomedical field, particularly for antibacterial and anticancer treatments. *Curcumin* nanoparticles exhibit better antibacterial activity than their conventional form and show better inhibition of cancer cell growth when combined with standard drugs (75). The synthesis method affects the characteristics of nanoparticles, with chemical reducing agents such as sodium borohydride producing smaller particles than bioreducing agents (105). Nanoparticles also show potential in cancer diagnosis, with various nanoparticles being developed for the delivery of targeted diagnostic and therapeutic agents to cancer sites, potentially improving efficacy and reducing side effects (103).

Environmental Field

Plant-based nanoparticles have become the focus of attention in efforts to preserve the environment, given the great potential they offer for creating eco-friendly solutions. By utilizing abundant and renewable biological resources, nanoparticles offer high efficiency in their application and are able to reduce negative impacts on the ecosystem. Therefore, plant-based approaches can be an innovative alternative in addressing various environmental challenges, such as waste treatment, water quality restoration, and supporting renewable energy efforts.
Based on **Table 2.**, several plant species were found that can be used in the synthesis of nanoparticles to be applied in the environmental field, namely *Moringa oleifera* to maintain water sterility from bacteria and nitrate contamination (91), *Citrus sinensis* which functions in purifying water from heavy metals (92), as well as degrading methylene blue dye pollutants based on *Cynometra ramiflora* (93) and *Brassica oleracea* var. Botrytis (94). Nanoparticles synthesized from such plants generally have sizes between 3-60 nm with varying shapes, such as spherical or rod-shaped, depending on the method and plant species used. These characteristics determine their stability and activity in environmental applications. These studies tend to focus on applications to keep water clean. Water cleanliness needs to be maintained because water pollution is a threat to animal or human health (106), can transmit pathogenic microorganisms (107), and reduce biodiversity (108). Water cleanliness can even affect social issues such as stunting (109) and the conduct of international swimming Olympics (110).
Nitrate pollution of waters is an increasingly widespread global problem (111). Nitrate pollution can originate from fecal contamination, livestock waste (112), agricultural pollution, and enhanced biogeochemical processes controlling water-rock interactions (113). Nitrate pollution in waters can result in eutrophication leading to widespread hypoxia and anoxia, loss of biodiversity, and harmful algal blooms that can damage ecosystems and pristine marine environments such as coral reefs (111). Nanotechnology is a superior alternative for nitrate removal compared to conventional methods because the small size of nanoparticles has a larger surface area and high reactivity, allowing their use as reducing agents as well as nitrate adsorbents (114). The selection of the type of nanoparticles that become nitrate reducers is crucial because some of them can fully reduce nitrate to nitrogen, while others only facilitate partial reduction (115). However, research conducted by Katata-Seru et al. did not show that FeNPs nanoparticles synthesized from *M. oleifera* extract were able to fully reduce nitrate to nitrogen, but still showed a decrease in nitrate concentration (91).
Heavy metals are toxic elements that are persistent in the environment, so they can accumulate in the food chain and cause negative impacts on human health and ecosystems (116). Heavy metal ion pollution in

water sources comes from municipal waste disposal (117). Heavy metal pollution can be reduced by the mechanism of adsorption, ion-exchange, and photochemical separation (118 ,119 ,120). Research conducted by Tavker et al. showed that the intensity of heavy metals polluted in waters can be reduced by combining 2 types of nanoparticles, namely ONPs and INPs synthesized from *Citrus sinensis* plants (88). ONPs and INPs have their own mechanisms in reducing heavy metal pollution. ONPs such as nano-fibrillated cellulose can reduce heavy metal waste through remediation, with adsorption alongside ion exchange mechanisms (121). While INPs are able to reduce heavy metal pollution through photocatalytic mechanisms, the photocatalytic capabilities of different metals allow for different binding via conversion of heavy metal species (122).

Decolorization and detoxification of industrial dye waste is a crucial aspect that is a top priority in meeting environmental standards and regulations (123). Waste dyes are considered highly hazardous because they contain parent compounds and degradation products with aromatic ring structures and reactive groups such as sulfur, naphthol, and nitrate, as well as heavy metals such as copper, arsenic, lead, cadmium, mercury, nickel, cobalt, and chromium (124). Methylene blue is a dye that is persistent, toxic, carcinogenic, and mutagenic (125) so needs to be broken down. Degradation of dye waste can use biological sources engineered into nanoparticles (126). Research by Bishnoi et al. (93) and Kadam et al. (94) showed that methylene blue dye can be degraded using INPs-type nanoparticles in the metal oxide and metal nanoparticles categories. Nanoparticles act as mediators in transferring electrons when degrading dyes (127). Nanoparticles can degrade dye effluents through a photocatalytic mechanism, where light (such as UV light or sunlight) induces the excitation of electrons in the nanoparticles, resulting in reactive electron-hole pairs (128). This reaction triggers the formation of reactive oxygen species (ROS) such as hydroxyl radicals (-OH) or superoxide ions (O_2--), which are capable of breaking chemical bonds in dye molecules, including aromatic rings and other reactive groups (129).

Another study found that nanoparticles can protect the environment through oil spill degradation, petroleum product spill control, reducing the accumulation of propylene oxide and other toxic by-products during the production of plastics, paints, and detergents (130). Not only limited to waste degradation, but nanoparticles can also be applied in renewable energy. Increasing the surface area to volume ratio of nanoparticles can improve solar energy collection and efficiency by exposing more conducting surfaces to sunlight (131). Despite the role of nanoparticles in the preservation of nature, nanoparticles entering the environment have adverse effects that can affect biotic and abiotic components (132). However, this possibility can be minimized through careful selection of nanoparticle size. In general, the larger the nanoparticle size, the lower the potential toxicity (133). Thus, research related to plant-based nanoparticles can continue to be explored to be developed into agents in preserving nature in the future.

Agricultural Field

Nanopesticides are compounds that kill insects, bacteria, and weeds, and are prepared on a nanometer scale using physical, physicochemical, and chemical methods. Nanopesticides are widely used as plant protection products with particle sizes <1000 nm. In a broad sense, nanopesticides are not limited to sizes between 10 and 100 nm (134). Some nanomaterials have specific antibacterial or insecticidal properties and can be used directly as active components in pesticides. Nanomaterials have many advantages in terms of their physical and chemical properties, small size, large specific surface area, and strong adsorption capacity, which enable them to be used as efficient pesticide carriers (135). Nanocarriers can improve the chemical stability and water dispersibility of pesticides, and at the same time protect the active ingredients from degradation by high temperatures and ultraviolet radiation in nature, thereby increasing their efficacy (136).

Based on **Table 2.**, iron oxide nanoparticles (IO–NPs) synthesized in an environmentally friendly manner using water extracts from the plant *Cissus quadrangularis* L. show great potential for development as natural pesticides. This plant contains bioactive compounds such as flavonoids, steroids, triterpenoids, and gallic acid, which act as reducing agents and stabilizers in the nanoparticle synthesis process. These nanoparticles exhibit a wide range of biological activities, including antioxidant, anti-inflammatory, cytotoxic, and anticancer properties. These mechanisms are highly relevant in the context of pesticide applications, as these effects can be adapted to inhibit the growth or kill plant pathogens and pests (95). **Table 2.** shows that silver nanoparticles (AgNPs) synthesized using dried *Pongamia glabra* leaf extract demonstrate significant potential as a natural pesticide, particularly as a biological fungicide. This study indicates that AgNPs produced through an environmentally friendly method are capable of inhibiting the growth and reproduction of the pathogenic fungus *Rhizopus nigricans*, which is known to cause post-harvest seed damage in various food crops. The main advantage of this approach is the use of locally available, inexpensive, and environmentally safe plant-based materials. Compared to synthetic chemical pesticides, AgNPs from *Pongamia glabra* offer a more ecological and sustainable solution for plant disease control, without causing toxic effects on human health or the environment (96).

CURRENT TREND

With advances in nanotechnology, nanoparticles can be used in all major fields to selectively target chemotherapy directly at cancer cells and neoplasms. Nanoparticles in cancer management can develop as drug-delivery vehicles (carriers), contrast agents (imaging), diagnostic devices, as well as diagnostic and therapeutic tools. Based on the data in **Table 1.**, it was found that the current trend or most research is focused on the use of plant-based nanoparticles for antibacterial and anticancer applications. Some information from the table is also supported by previous studies that have extensively addressed the topic of synthesizing plant-based nanoparticles for anticancer and antibacterial purposes

Gavamukulya's research on the mechanism of action of AgNP involves the activation of the intrinsic apoptosis pathway through increased regulation of CASP9 and decreased regulation of the CXCLI gene axis, indicating that biologically synthesized AgNP, particularly AgNP-F, can be used in the development of new anticancer drugs (62). In Ranjbar's study investigating the biological activity of nanoemulsions and nanogels containing *C. cyminum* essential oil, the results showed that luteolin-7-O-glucoside, a flavonoid in *C. cyminum*, exhibits anticancer activity. Additionally, *C. cyminum* demonstrates antibacterial activity against *P. aeruginosa* (137). Further supporting research was conducted by Sarti (2020), who synthesized silver nanoparticles that are potent and safer for anticancer and antibacterial applications based on *Taxus*, with research results showing that AgNP has dose-dependent biocompatibility and antibacterial effects that are slightly or more significant compared to silver nitrate solutions, and that silver nanoparticles synthesized from herbs can serve as an efficient alternative to silver nitrate-based drugs with fewer side effects (138). Silver nanoparticles synthesized using *Ammi visnaga* extract in Farooq's (2023) study showed 99% inhibition against biofilms and bacteria, excellent anticancer activity with an IC50 concentration of 17.1 ± 0.6 µg/mL, and 100% inhibition. Therefore, the synthesized silver nanoparticles can be used in the treatment of wastewater contaminated with toxic dyes, pathogenic biofilms, and cancer cell treatment (139).

Combining green chemistry and nanotechnology is an effective approach, as extracts from the leaves of *Cassia fistula* can demonstrate strong antibacterial activity with antimicrobial action from CF-SNP tested against *E. coli* DH5-Alpha. In anticancer activity tests, the synthesis of antibacterial silver nanoparticles

(CF-SNP) showed greater anticancer properties than CF-GNP. Therefore, researchers hope that this engineered CF-SNP can be used for more effective treatment of cancer cells (140). By leveraging the anticancer and antibacterial properties of *Scutellaria barbata*, Jetti's (2024) research demonstrated that a new ultrasonic preparation of nano-lipid carriers enhances bioavailability and controlled release of the extract, which is crucial for the therapeutic efficacy of the disease being treated (141).

Thus, research conducted between 2023 and 2024 shows that plant-based nanoparticle synthesis mostly produces inorganic nanoparticles (INPs). These studies predominantly apply plant-based INPs for anti-cancer and antibacterial therapy. Therefore, the biological synthesis of herbal-based nanoparticles using secondary metabolites or biomolecules involved in reduction and stabilization derived from plants can enhance drug targeting to cancer cells in a more stable manner and facilitate easier access to target cells.

FUTURE PROSPECT OF NANOPARTICLES

To advance modern nanotechnology, secure, practical, and environmentally friendly methods of synthesizing nanomaterials are required. However, chemical techniques generally still use hazardous materials and produce toxic waste that can pollute water, air, and soil and endanger living creatures. As an alternative, plants can be used for safer and more economical nanoparticle synthesis. In addition to supporting sustainable bioenergy, this approach also reduces environmental risks. Nevertheless, nanotechnology still raises concerns due to the potential toxicity of nanoparticles in the environment (142).

Nanoparticles offer a very promising future and cover a wide range of fields. The development of this technology is increasingly focused on green synthesis approaches based on plants, which are considered more environmentally friendly, cost-effective, and capable of producing nanoparticles with high biocompatibility. Currently, the use of nanoparticles, particularly plant-derived biosynthetic silver nanoparticles, is widely utilized in cancer therapy due to their ability to specifically and efficiently recognize and target cells. As in previous research by Netala which discussed the biosynthesis of silver nanoparticles (IH-AgNPs) using leaf extracts from *Indigofera hisruta* L., the results showed three distinct biological activities (a 3-in-1 system), including antimicrobial activity, activity against various free radicals, anticancer activity against cancer cells, and biocompatibility with normal cells (143).

In addition, research conducted by Kumari (2019) investigated the synthesis of silver nanoparticles (AgNPs) through the bioactive fraction of *Pinus roxburghii* plants using a simple, cost-effective, and environmentally friendly green chemistry method, with results showing that PNb–AgNPs are capable of inducing cancer cell death and can act as a therapeutic nanoformulation for cancer (144). Furthermore, the application of nanoparticles is rapidly expanding in the fields of pharmacy, agriculture, the environment, and cosmetics, thanks to their ability to enhance the efficiency, safety, and stability of formulations. However, challenges such as low reproducibility and the need for long-term toxicity studies remain a concern. However, technological advancements such as microfluidics and Surface-Assisted Laser Desorption/Ionization Mass Spectrometry (SALDI-MS) offer potential solutions to overcome these obstacles.

CONCLUSION

The development of plant-based nanoparticle synthesis has shown significant progress and opened great opportunities in various fields of sustainable application. This approach utilizes bioactive compounds from plant extracts as reducing and stabilizing agents, thereby replacing conventional synthesis methods that typically involve hazardous and potentially toxic chemicals. In the field of health, metal nanoparticles such as silver nanoparticles (AgNPs) synthesized from the plants *Lawsonia inermis*, *Aloe vera*, and *Curcuma longa* have demonstrated high efficacy as antimicrobial, anti-inflammatory, antioxidant, and anticancer agents, with good biocompatibility and specific cellular targeting capabilities. In the agricultural sector, the synthesis of green nanoparticles such as FeNPs from *Cissus quadrangularis* produces natural pesticide alternatives that are not only environmentally friendly but also have broad biological efficacy against pests and plant pathogens. Meanwhile, in the environmental field, the use of plants such as *Moringa oleifera* and *Citrus sinensis* in nanoparticle synthesis has shown great potential in addressing water pollution, particularly in reducing heavy metal levels, nitrates, and industrial dye compounds through adsorption and photocatalytic degradation mechanisms. Plant-based nanoparticles also contribute to the development of renewable energy by enhancing solar energy absorption efficiency. Thus, plant-based synthesis approaches are considered promising as innovative, sustainability-oriented solutions in the health, agriculture, and environmental sectors.

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CONFLICT OF INTERESTS

The author declares no conflict of interest regarding the publication of this article.

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