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Biosynthesis of Nanoparticles using *Pongamia pinnata* and its Application - An Updated Review

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Abstract: Nanotechnology is a rapidly developing field with potential applications across a wide range of industries, including cosmetics and medicine. Nanoscience is the study that focuses on developing materials with unique properties at the nanoscale. The characteristics of such materials are related to their sizes and differ significantly from those of bulk substances. Nanoparticles have outstanding physical and chemical properties, which have gained the interest of researchers. As a result, they have gained attention in various domains such as biomedical, environmental, and energy applications. In the last few decades, a leguminous tree species, i.e., *Pongamia pinnata*, has gained significant importance due to its capability as a renewable source of biofuel and various other applications. *Pongamia pinnata* is also known by the name Indian beech, or more commonly, karanj. It is one of those medicinal plants in which everything has been utilized as a systematic drug worldwide for the treatment of various kinds of health issues, such as piles, skin disorders, and wounds. This review provides an in-depth overview of the current status of research on the eco-friendly production of nanoparticles from Pongamia pinnata and the diverse applications of *Pongamia pinnata*-derived nanoparticles.

Keywords: *Pongamia pinnata*; green synthesis; nanoparticles; top-down; bottom-up

1. Introduction

Nanoscience and nanotechnology, involving various nanostructures, are among the considerations of growing disciplines. Due to the advancement of human civilization, it is expected to hold significant economic potential in the days to come [1]. In 1974, Norio Taniguchi first coined the word nanotechnology [2]. Nanoparticles are defined as particles with 1 dimension of ~100 nm and are considered to be fundamental units of nanotechnology. In nanoscience, materials are prepared at the nanoscale by exploiting certain properties [3]. In the twenty-first century, a specialization in nanoscience known as nanobiotechnology has been regarded as critically important for addressing specific issues in electronics, medicine, and agriculture [4]. It is a rapidly emerging field and has numerous scopes in the industry, including the cosmetic and medical fields. The science and technology of synthesizing materials with special functions at the nanoscale are relatively cost-effective, given their wide range of applications across industries. The properties of nanomaterials are size-related and are not similar to those of bulk materials [3]. Nanotechnology aims to observe, control, and manipulate structures and materials operating at the nanoscale [5]. Some nanoparticles have toxicity or stability issues that limit their use, despite their distinctive chemical and physical properties; their biomedical and environmental applications are often limited [6]. By combining two nanomaterials, a hybrid nanocomposite with enhanced capabilities can be formed, overcoming the limitations of individual nanoparticles. Bimetallic nanocomposites have become an epicenter of research due to their potential to exhibit antimicrobial activity, anticancer properties, highly selective and sensitive detection, biodegradability, stability, and enhanced drug encapsulation efficiency [7-9].

According to previous literature, biomolecules and living organisms can be used as stabilizing and reducing agents to produce various types of nanomaterials [10]. In terms of synthesis, nanomaterials are generally produced via biological/chemical methods, reducing the metal concentration to metal atoms, which are then divided into physical, chemical, or a combination of both (Figure 1). Biological synthesis of nanoparticles is important because it is an environmentally friendly, cost-effective, and scalable green alternative to traditional chemical methods, which often use toxic materials. This approach offers control over nanoparticle properties, such as size and shape, for specific applications in medicine, and can produce nanoparticles with improved biocompatibility and reduced toxicity. Biological methods avoid the use of harsh and toxic chemicals typically used in traditional synthesis. They utilize readily available and inexpensive resources like plants and microorganisms, which reduces overall production costs. They are suitable for large-scale production, increasing the potential for industrial application.

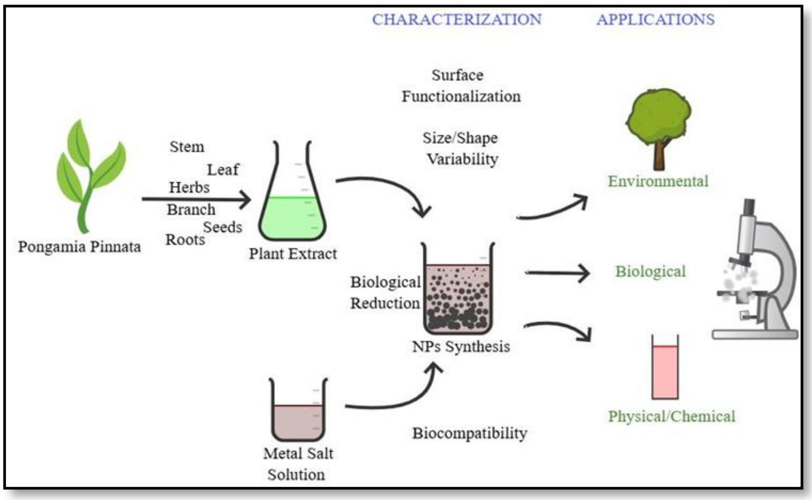

Figure 1. Process of synthesizing nanoparticles from *P. pinnata* plant extract and their applications.

The biological or green synthesis approach is an efficient means of synthesis that uses biological systems that are environmentally friendly, cost-effective, and low-toxic, such as plant extracts or microbes (bacteria, fungi, yeast, or viruses) as reducing and stabilizing agents. Chemical synthesis is a controlled process in which reducing agents (usually chemicals) are used to reduce and stabilize the reactants. Due to environmental concerns, researchers are now focusing on more environmentally friendly synthesis techniques rather than solely on physical and chemical methods. Exploration of natural resources holds promise as a sustainable alternative to techniques that rely on physical and chemical methods. The green method minimizes the use of harmful compounds in the synthesis process [11]. The biological method using plants or plant-derived products is becoming increasingly popular due to its ease of use, environmental friendliness, and broad antibacterial activity. It has been reported that plants, including *Pleurotus barbatus*, *Aloe vera*, *Laurus nobilis*, and *Pongamia pinnata*, can be utilized in the synthesis of various nanoparticles [4, 12]. Plant extracts offer a more environmentally friendly method for producing multiple metallic nanoparticles, allowing for a regulated synthesis with precisely defined nanoparticle size and form [13]. Furthermore, better performance of the nanomaterials can also be achieved by properly selecting metal combinations and optimizing the conditions of each metal. Nanomaterials are widely tested in biomedical systems to improve human health and in the environment to degrade toxic compounds [14].

Pongamia pinnata belongs to the family "Leguminosae". It is extensively found in Southeast Asia, tropical Asia, the Seychelles Islands, India, and Australia. It is also found locally in the Indian state of Maharashtra along riverbanks; it is widespread close to the coastal tidal and beach forests in the Konkan and along the Deccan rivers. *Pongamia pinnata* contains a variety of phytochemicals, including alkaloids, flavonoids (such as kaempferol and quercetin), glycosides, fixed oils, and carbohydrates. Other compounds include tannins, saponins, and terpenoids, with specific compounds like karanjin, pongamol, and pongapin found in its leaves and seeds. These compounds contribute to the plant's diverse medicinal properties, such as its antioxidant, anti-inflammatory, and antimicrobial activities. CNS depressive activity, antiplasmodial, antinociceptive, anti-hyperglycaemic, anti-lipidoxidative, antidiarrheal, anti-ulcer, and antihyperammonic [12,4]. Both conventional and modern medicine continue to benefit from the useful therapeutic compounds that medicinal plants offer [15,16]. As a crude medication, *Pongamia pinnata* has been deployed to treat ulcers, piles, skin conditions, and tumors. The roots of karanj are effective for the treatment of gonorrhea, cleaning gums, teeth, and ulcers, and are used in vaginal and skin diseases. There are several applications of seed oil, but it is particularly useful for treating rheumatism, leucoderma, scabies, and ulcers [17]. This review provides an overview of the current status of research on eco-friendly production of nanoparticles using *Pongamia pinnata* and its applications in various fields.

2. Methodology

Various approaches used for synthesizing nanoparticles are described below in Figure 2.

2.1. Bottom-up.

It is a procedure in which the substances convert atoms into clusters, forming nanoparticles. The most widely used bottom-up nanoparticle synthesis methods are biosynthesis, pyrolysis, chemical vapor deposition (CVD), sol-gel, and spinning.

A sol is a colloidal dispersion in which components are suspended in a liquid medium. A gel is formed when a solid macromolecule is dispersed in a solvent. The Sol-Gel method is utilized to synthesize nanoparticles due to its ease of use and ability to produce various types of nanoparticles. This wet chemical technique uses an organic solution as a starting material to form an integrated system of discrete particles. In this method, the most widely used starting materials are metal oxides and chlorides [18]. A chelating agent cum polymer, which was used in the study, has been able to lead the sol-gel method for the synthesis of spinel $NiFe_2O_4$ nanoparticles. Produced spinel $NiFe_2O_4$ powders at low temperatures and good stoichiometric control [19].

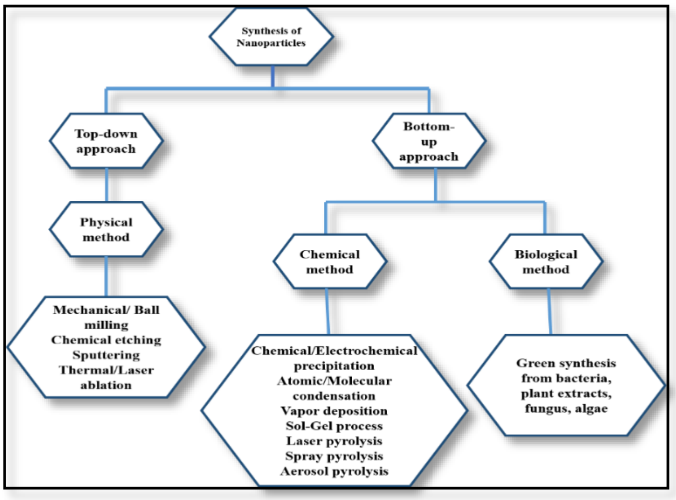

Figure 2. Approaches are used to synthesize nanoparticles.

A chelating agent cum polymer, which was used in the study, has been able to lead the sol-gel procedure for the synthesis of spinel $NiFe_2O_4$ nanoparticles. Boyle spinel $NiFe_2O_4$ powders at comparatively low temperatures and good stoichiometric control [19]. In contrast to the routine method that has been used procedural o Spinel $NiFe_2O_4$ the thermal elimination of polymeric hybrid materials – spinning disc reactor (SDR). A spindle comprising a bore and a wind rotor in a physical reactor, where rotational force can control variables such as temperature and pressure through rotational force, can respond to changing stresses. Inert gases, such as nitrogen, are commonly injected into the reactor to prevent unwanted reactions. The disc has multiple liquid feed ports, as water, a co-rotating magnetic drum type, and a non-rotating deicer are fed into the reactor, slowly atomizing the liquid [18]. Mohammadi *et al.* have systematically demonstrated the sol-gel process of titanium dioxide in a spinning disc reactor (SDR), varying parameters to narrow the particle size distribution (PSD) and yield smaller, more uniform particles [20].

In CVD, a thin layer of gas-phase reactants is deposited onto a substrate. By combining gas molecules at room temperature, the substrate is deposited in a chamber. After coming in contact with the combined gas, the heated substrate causes a chemical reaction [19]. Nakaso utilized an electrospray-assisted CVD technique to create SiO_2, TiO_2, and ZrO_2 nanoparticles [21, 22]. To compare with the ES-CVD process, these particles were also generated using a traditional evaporation CVD method. The most widely used industrial method for generating nanoparticles on a large scale is pyrolysis, in which a precursor is heated to convert it. The precursor is injected into the furnace, operating at maximum pressure, through a tiny hole, where it burns and can exist as either vapor or liquid. To get the nanoparticles back, the burning by-product gases are air-categorized. Some furnaces use lasers to raise the temperature to a point where simple evaporation can occur, rather than using flames [18].

A safe, environmentally friendly method for creating nontoxic, biodegradable nanoparticles is to use biological materials [18,22].

2.2. Top-down.

This method is referred to as breaking down bulk materials into nanoscale particles. The most commonly employed techniques for synthesizing nanoparticles include sputtering, thermal decomposition, laser ablation, nanolithography, and mechanical milling.

Mechanical milling is a simple, affordable, and high-yield technique and can produce various nanomaterials [23]. However, to achieve stable or metastable phases, the process parameters must be carefully controlled. Additionally, controlled thermal treatment may be helpful after mechanical activation to produce the ideal materials [24].

Nanolithography is a technique for fabricating nanoscale structures, with one dimension in the size range of 1-100 nm [18]. There is a wide range of nanolithography techniques, including optical, electron-beam, multiphoton, nanoimprint, and scanning probe lithography.

Laser Ablation Synthesis (LASiS) is a frequently used technique to produce nanoparticles from different solvents. The plasma plume condenses and forms nanoparticles when a metal immersed in a fluid mixture is exposed to a laser beam [18]. The main benefits of laser ablation include its simplicity, speed, and effectiveness in producing a range of nanoparticles without the need for dangerous or toxic chemicals, and, when used in water, it can produce ultrapure colloidal solutions [25, 26].

Sputtering is a process of leaving behind nanoparticles on a surface by ejecting them via ion collisions [18]. The shape and size of the nanoparticles are determined by several factors, including the type of substrate, annealing temperature, duration, and layer thickness, which are typically achieved through sputtering followed by annealing [18, 27].

A substance undergoes thermal decomposition, or an endothermic chemical process, when its chemical bonds are broken by heat [18]. The decomposition temperature is the exact temperature at which an element experiences chemical disintegration. At these specific temperatures, the metal decomposes, triggering a chemical reaction that produces secondary compounds that facilitate the formation of nanoparticles [28].

3. Nanoparticles Classification

Nanoparticles (NPs) are distinguished by their chemical compositions, shape, and size. Based on these parameters, they are classified as carbon-based, metal nanoparticles, lipid-based, semiconductor, and polymeric nanoparticles.

3.1. Carbon-based nanoparticles.

Carbon-based nanoparticles are a class of nanomaterials that include structures such as graphene, fullerenes, and carbon nanotubes. They are known for their unique chemical and physical properties, such as electrical conductivity, high surface area, and biocompatibility. Carbon-based nanoparticles have greater hydrophobic interactions than graphene and nanoplastics, such as MWCNT, which demonstrated increased adsorption of pyrene and bisphenol A. Compared with graphene, pyrene uptake on carbon nanotubes and nanoplastics increased more with higher equilibrium concentrations, most likely because of graphene's open-layer structure. Because of their larger surface area, carbon-based adsorbents such as graphene, carbon nanotubes, and activated carbon were able to adsorb phenanthrene 1.5–2 times more efficiently than microplastics [29].

3.2. Metal nanoparticles.

Metal nanoparticles are nanomaterials that are made up of one element, which includes Au, Ag, Cu, Pt, Pd, Zn, Re, etc. Organic ligands, including thiols, phosphines, and amines, can be used to synthesize and stabilize metal nanoparticles. Surface characteristics, such as morphology and metal content, of metal oxide nanoparticles (NPs) can affect their biological capabilities, including antibacterial, anticancer, and catalytic activities [14]. These are very small pieces composed of inorganic, non-metallic, and non-organic matter that are later subjected to a specific thermal cycle to improve their properties. These types of nanoparticles are characterized by their long-term stability and resistance to heat, and they can be amorphous, polycrystalline, dense porous, or hollow. Michala and other researchers are working on ceramic nanoparticles for diverse applications - batteries, catalysts, coatings, etc. [30]. They produced chiral tungsten oxide (WO3-x) ceramic nanoparticles utilizing chiral ligands L-Asp, D-Asp, L-Pro, and D-Pro. These NPs have been characterized using various techniques, including mass spectrometry, TEM (Transmission Electron Microscopy), XRD (X-Ray Diffraction), XPS (X-ray Photoelectron Spectroscopy), UV-Vis (Ultraviolet-Visible Spectroscopy), MCD (Magnetic Circular Dichroism), FTIR (Fourier-Transform Infrared Spectroscopy), and Raman scattering.

3.3. Lipid-based nanoparticles.

Lipid NP are nanometer-sized vesicles made up of lipids that are utilized for delivery systems such as mRNA, drugs, and other bioactive compounds. These particles are known for their biodegradability, biocompatibility, and ability to protect their payload during transport [30]. Tumor-targeted therapies that utilize the biocompatible lipid nanoparticles, however, do not rely on photosensitive materials, whose disadvantages are well known. Therapeutic approaches using combined lipid nanoparticles enable photochemotherapy. Studies with lipid-based photoresponsive nanoparticles have demonstrated that tumor targeting and, consequently, therapeutic efficacy are improved, making these forms particularly favorable for cancer therapy [31].

3.4. Semiconductor nanoparticles.

Semiconductor nanoparticles share characteristics with both metals and non-metals. Therefore, semiconductor NPs have chemical and physical characteristics that enable a wide range of applications [30]. Lead selenide (PbSe) nanoparticles were effectively synthesized by utilizing *Trichoderma* sp. WL-Go fungus was used both as a capping and reducing agent. The synthesized PbSe nanoparticles were characterized and found to be cubic, ranging in size from 10 to 30 nm, capped with proteins, and secreted by the fungus. PbSe nanoparticles had strong photocatalytic activity, destroying 82% of rhodamine B dye in 30 minutes, and strong antioxidant activity, eliminating up to 88.60% of free radicals [32].

3.5. Polymeric nanoparticles.

Active ingredients are surface-adsorbed onto the polymeric core of nanoparticles (NPs) ranging in size from 1-1000 nm, or they may become trapped inside the polymeric body. The term polymer nanoparticle (PNP) is frequently used to refer to such kinds of NPs, which are organic and resemble nanospheres or nanocapsules [30]. Diko provided an overview of the use of polymeric nanoparticles as drug-delivery carriers for cancer treatment [32]. It also discussed various types of nanoparticles that are being used, their advantages over traditional treatment modalities, and the mechanisms of targeted delivery to tumor cells.

4. Applications of Biosynthesized Nanoparticles using *Pongamia pinnata*

Biosynthesized nanoparticles derived from *Pongamia pinnata* have exhibited notable applications as they possess biological, environmental, and agricultural applications (Figure 3) (Table 1). In a study, AgNPs synthesized from *Pongamia pinnata* leaf extract showed antibacterial activity against *Escherichia coli*, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, and *Klebsiella pneumoniae* [4]. Another study reported gold nanoparticles (AuNPs) synthesis using *Pongamia pinnata* leaf extract, which demonstrated antifungal efficacy against oomycetes SR1 and BP1120, with MIC80 values of 1.6 and 0.8 mg/mL, respectively [33]. Furthermore, AgNPs synthesized from the seed extract of *Pongamia pinnata* exhibited synergistic effects with ampicillin against *E. coli* ATCC 25922, indicating their potential use in tackling antibiotic-resistant bacteria [10] (Table 1).

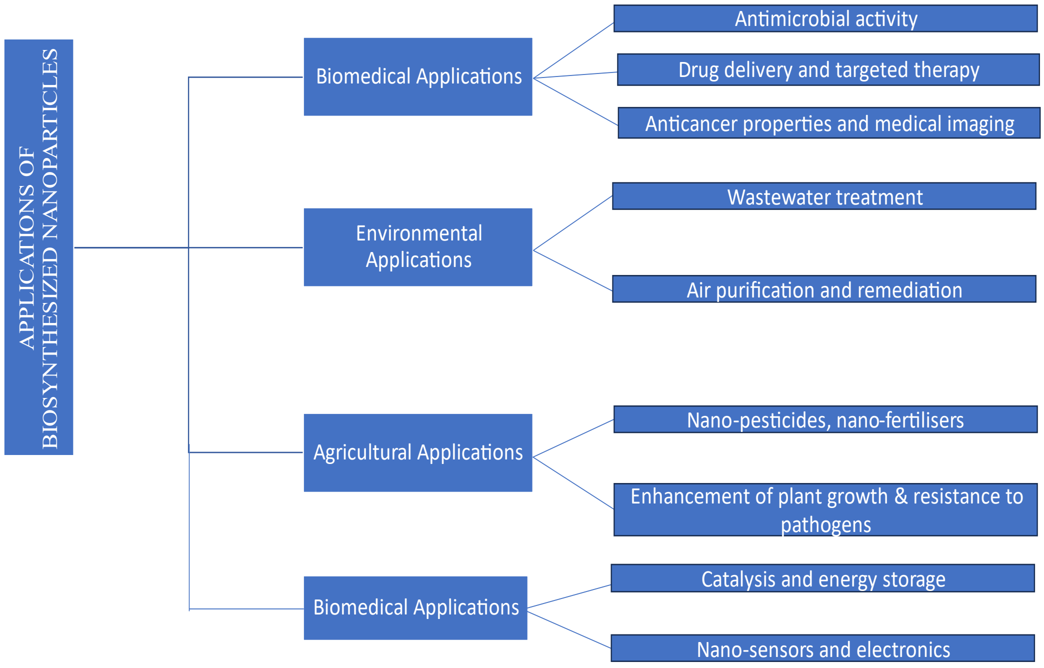

Figure 3. Biosynthesized nanoparticles using Pongamia *pinnata*.

4.1. Biological applications.

Pongamia pinnata exhibits strong antimicrobial activity against various pathogens. Silver nanoparticles synthesized using *Pongamia pinnata* bark extract exhibited antibacterial effects on both gram-positive and gram-negative bacteria, with the highest inhibition observed against *Klebsiella planticola* (15 mm) and the lowest against *Staphylococcus aureus* (13 mm) at a concentration of 100 µg/ml [3]. The ethyl acetate seed extract displayed strong antimicrobial activity against several test pathogens, with *Staphylococcus epidermidis* being the most susceptible strain (MIC/MBC 1.56/3.12 mg/ml) [34]. The crude aqueous seed extract of *Pongamia pinnata* completely inhibited the growth of herpes simplex virus types 1 and 2 at concentrations of 1 and 20 mg/ml, respectively [35]. Nevertheless, the leaf decoction reduced cholera toxin production and bacterial invasion of epithelial cells, suggesting a specific antidiarrheal effect against cholera and enteroinvasive bacterial strains [36]. A study reported antioxidant activity of silver nanoparticles derived from *Pongamia pinnata* leaf extract and suggested that they may be essential for preserving health against oxidative stress-related degenerative diseases, such as cancer [37]. Another study reported the synthesis of zinc oxide nanoparticles using *Pongamia pinnata* and its antibacterial activity against *Staphylococcus aureus* and *Escherichia coli* [38]. Yadav *et al.* reported silver nanoaprticles synthesis using *Pongamia pinnata* methanolic extract and evaluated its application as an antifertility agent on male rats [3]. For 60 days, male rats were orally administered AgNPs, and the testicular tissue was subsequently examined using TEM. TEM analysis revealed significant alterations in the seminiferous tubules, including vacuolization, disorganized germinal epithelium, and mitochondrial damage, indicating impaired spermatogenesis [3]. A study reported the synthesis of SrO nanoparticles using *Pongamia pinnata* and evaluated their dose-dependent antibacterial activity against *Streptococcus pneumoniae*. It also exhibited moderate anti-inflammatory and strong antioxidant activity [39].

4.2. Environmental applications.

Nanoparticles have attracted considerable interest due to their potential applications in wastewater treatment, especially for eliminating heavy metal ions and dyes. Different types of nanoparticles, such as carbon-based materials, metal oxides, and those synthesized using green methods, have demonstrated promising effectiveness in this area. These nanoparticles possess remarkable adsorption capabilities and antimicrobial properties, making them highly efficient for contaminant removal [40]. A study reported the synthesis of zinc oxide nanoparticles using this plant, which has shown promising results in environmental remediation, particularly in removing heavy metal ions and dyes from wastewater [3-42]. These nanoparticles, synthesized using green methods, offer benefits such as eco-friendliness and reduced dependence on non-renewable resources. A study reported *Pongamia pinnata*-induced silver nanoflowers for the degradation of malachite green dye [41]. Devi *et al*. synthesized nanoparticles using *Pongamia pinnata* leaf extract (PPLE) and observed that, upon solar irradiation of the solution containing the nanoparticles, the nanoparticles and dyes undergo plasmonic decay without radiation emission [4]. The dye was excited and produced electrons, while the PPLE-NPs absorbed photons, resulting in excited electrons in the conduction band. The electron's potential energy increased during this process, preparing it for further reactions.

Table 1. Applications of *Pongamia pinnata*-derived nanoparticles.

Nanoparticle	Plant material utilized	Application	Size and shape	Reference
AuNPs	Leaves extract	Anticancer activity	18 nm, histogram	[5]
Si	leaves extract	Antioxidant	12 nm	[43]
Ag	leaves extract	Antioxidant	19 nm	[44]
Ag	seed extracts	Antimicrobial activity	15 nm	[10]
Ag	leaves extract	Antimicrobial activity	40 nm, spherical	[45]
Ag	leaves extract	Anti-inflammatory activity	200 nm, spherical	[46]
Cu	flower	Anti-inflammatory activity	23 nm	[47]
Ag	leaves extract	Cytotoxicity assay	200 nm	[17]
Ag	seed extract	Antibacterial activity	30 nm, spherical	[10]
Zn	leaves extract	Antibacterial activity	100 nm, spherical	[13]
Cu	leaves extract	Antibacterial activity	23 nm	[47]
Ag	flower extract	Anti-cholinesterase activity	49 nm, spherical	[3]
Bi	Pods	degradation of water pollutants	25 to 70 nm	[17]

4.3. Agricultural applications.

Nanotechnology has demonstrated promising applications in agriculture, especially in the development of nanofertilizers and nanopesticides. The leguminous tree *Pongamia pinnata* has been investigated for its ability to produce nanoparticles beneficial for agricultural purposes [4,48]. Silver nanoparticles generated from the leaf extract of *Pongamia pinnata* have shown effectiveness against a range of bacterial strains such as *E. coli*, *S. aureus*, *Ps. aeruginosa*, and *K. pneumoniae*. This environmentally friendly synthesis method is economical and has potential applications in the formulation of nanopesticides. Furthermore, compounds derived from Pongamia pinnata seeds, including pongarotene and karanj, have shown antifungal and antibacterial activity and may be further investigated for use in nanopesticides. Compared to traditional agrochemicals, nanofertilizers and nanopesticides offer numerous benefits, including enhanced nutrient utilization, targeted application, and reduced environmental impacts [49,50]. Nanoparticles can serve as "magic bullets," incorporating nanopesticides and nanofertilizers that target specific organelles within plant cells [43]. It is essential to assess the economic and environmental advantages of these nanoformulations to guarantee their sustainable integration into agricultural practices [50].

4.4. Industrial applications.

Pongamia pinnata has emerged as a promising candidate for biodiesel and renewable energy production. The transesterification of *Pongamia* oil using base-catalyzed methods has improved fuel properties and engine performance. A study indicated that blends of *Pongamia* methyl ester with diesel, specifically at 15-20% (B15 and B20), improved brake thermal efficiency and reduced brake-specific fuel consumption, particularly under higher loads [50]. Another investigation used crude karanja oil (CKO) derived from *Pongamia pinnata*, achieving an 84% conversion rate via a one-step transesterification process, with optimal performance observed in a B40 blend [52].

5. Challenges in the Biosynthesis of Nanoparticles

The production of nanoparticles using Pongamia pinnata extracts faces several challenges related to scalability and economic viability. Although the green synthesis method utilizing *Pongamia pinnata* is sustainable, transitioning to industrial-scale production presents challenges. Various factors, such as pH, temperature, and precursor concentration, significantly impact nanoparticle characteristics and size, posing challenges for consistent production in large-scale manufacturing [53]. Furthermore, it is crucial to standardize procedures and optimize conditions to maximize yield, making the process economically feasible [10]. Some research has indicated potential advancements in scalability. For example, scientists enhanced gold nanoparticle production using Pongamia pinnata seed cake extract via response surface methodology, resulting in a twofold increase in nanoparticle output [10]. This implies that employing systematic optimization methods can improve both yield and efficiency. Variability in the composition of plant materials can influence both nanoparticle synthesis and their properties. Various studies have employed different parts of *Pongamia pinnata*, including bark [3], seeds [10], and leaves [4], to produce nanoparticles. The bioactive compounds that facilitate reduction and stabilization may vary among plant parts and across different batches, which can affect the consistency of results when scaling up [4,33]. It is crucial to optimize the reaction conditions for large-scale manufacturing. Key factors such as pH, extract concentration, temperature, and reaction duration need to be meticulously controlled to enhance yield and quality [52]. For example, the synthesis of gold nanoparticles was fine-tuned to a pH of 3.6 and an extract concentration of 17.07% [52]. A similar approach to optimization would also be required for silver and other types of nanoparticles.

The toxicity of nanoparticles can be affected by factors that go beyond their composition. For AgNPs synthesized from *Pongamia pinnata* seed extract, research into their interaction with human serum albumin aimed to shed light on possible influences on bioavailability and distribution. The findings indicated only slight alterations to the protein's structure upon binding [4]. However, other research has demonstrated that nanoparticle toxicity can be notably influenced by the cellular environment. For instance, the presence of serum proteins in cell culture media can lead to the formation of a protein corona around nanoparticles, altering their biological interactions and toxicity [54]. The environmental factors and proper disposal of these nanoparticles are not thoroughly discussed. This is a crucial area that requires further research, as the growing use of nanoparticles across numerous applications may lead to their accumulation in ecosystems. The papers mainly concentrate on the synthesis, characterization, and possible uses of the nanoparticles, while neglecting to explore their long-term environmental effects or disposal strategies.

6. Future Directions

Future research directions and trends in optimizing synthesis methods for nanoparticles derived from *Pongamia pinnata* emphasize improving extraction methods and refining synthesis protocols. Scientists are examining methods to improve the efficiency and sustainability of nanoparticle production utilizing *Pongamia pinnata* extracts. Innovations in extraction and synthesis methodologies are focusing on optimizing reaction parameters such as pH, temperature, and extract concentration. For example, a research applying response surface methodology (RSM) revealed that adjusting pH and the concentration of *Pongamia* seed cake extract led to a two-fold increase in gold nanoparticle production [52]. Furthermore, researchers are investigating the specific phytochemicals involved in the formation and stabilization of nanoparticles, which may lead to more targeted extraction techniques [64]. Researchers have investigated different parts of the plant, such as leaves, bark, and seeds, for the synthesis of nanoparticles [4–3,52]. One strategy to improve both yield and consistency is by fine-tuning the reaction parameters.

Nanoparticles are increasingly being investigated for their potential applications in personalized and regenerative medicine. They possess distinct characteristics that can be utilized for targeted drug delivery, tissue engineering, and cell therapy [56,57]. For example, nanofibrous materials are being created as scaffolds for tissue engineering across different organs, replicating the natural extracellular matrix and enhancing cell adhesion [56]. Carbon nanoparticles, including graphene and carbon nanotubes, have shown potential for use in medical diagnostics, bioimaging, and drug delivery, although clinical use remains limited due to concerns about toxicity [57]. Extracellular vesicles (EVs), which are naturally occurring biological nanoparticles, are gaining attraction as effective 'cell-free' nanotherapeutics for tissue engineering and regenerative medicine [58,59]. These EVs can be 3D bioprinted for precise delivery and to address regulatory and cost-efficiency challenges linked to the use of living cells [58].

7. Commercialization and Regulatory Challenges

The commercialization and regulatory obstacles to green nanotechnology, especially for nanoparticles derived from *Pongamia pinnata*, encompass several critical factors. Green nanotechnology, which employs plant extracts such as *Pongamia pinnata* for the synthesis of nanoparticles, offers substantial opportunities for environmentally friendly nanomaterial production [60]. The journey toward commercialization is impeded by challenges related to safety regulations and acceptance in the marketplace. Regulatory agencies are currently developing guidelines to assess the safety and risks associated with nanomedicine products, underscoring the need for standardized characterization methods [61]. This is especially important for plant-derived nanoparticles, whose distinct properties and potential interactions with biological systems require comprehensive evaluation. Although green nanotechnology seeks to minimize environmental effects, it continues to encounter similar regulatory oversight as traditional nanomaterials. The intricate nature of nanoparticles as three-dimensional constructs demands meticulous design, engineering, and reproducible scaling to produce consistent products with desired physicochemical traits and biological responses [62]. This intricacy presents challenges in adhering to regulatory requirements and guaranteeing product uniformity at commercial levels. To tackle these issues, a comprehensive strategy is essential. It is vital to facilitate collaboration among regulatory agencies, researchers, and industry stakeholders to create suitable safety evaluation approaches for plant-based nanoparticles [61, 62]. Investing in data systems and automation can help organizations navigate complex regulatory landscapes more effectively [63]. Furthermore, promoting transparency and ensuring consistent enforcement will be crucial to cultivating trust in these innovative technologies and encouraging their market acceptance [63]. As the field evolves, adaptive regulations that keep pace with technological developments will be vital to balancing innovation and safety concerns in the commercialization of green nanotechnology products, such as nanoparticles derived from *Pongamia pinnata*.

The commercialization and mass production of nanoparticles derived from *Pongamia pinnata* present various challenges and opportunities. *Pongamia pinnata*, a rapidly growing leguminous tree, has demonstrated the potential for significant oilseed yield and can thrive on marginal lands, making it an ideal candidate for large-scale vegetable oil production for the biodiesel sector [61]. Nevertheless, effectively bringing this technology to market necessitates a thorough understanding of the plant's genetics, physiology, and propagation methods. A primary obstacle to the industrial use of *Pongamia pinnata*-based nanoparticles is the need for reliable, scalable manufacturing processes. As with other nanoparticle technologies, variations between batches and inconsistent product performance during scale-up manufacturing pose significant challenges [64]. To address these issues, researchers must focus on developing scalable, resilient manufacturing methods that enable the transition of production from laboratory settings to industrial scales.

8. Conclusion

The use of “*Pongamia pinnata*” for the synthesis of nanoparticles offers an effective and environmentally friendly approach. Plant extracts can be used to synthesize eco-friendly, cost-effective, and stable nanoparticles, such as silver, zinc, and copper nanoparticles, which have potential biomedical applications due to their significant antioxidant, anti-cholinesterase, and antibacterial activities. The plant is rich in phytochemicals, which possess medicinal properties and can also be used as a stabilizing agent for nanoparticle synthesis. These nanoparticles are effective for reducing water pollution from heavy metals, degrading dyes, and remediating pesticides. The extracts also exhibit several biological activities, including antibacterial, antiviral, antiulcer, antidiarrheal, antioxidant, and antimalarial activities, thus declaring "Pongamia pinnata" an asset for environmental and medicinal applications. The plant also holds significance in sustainable technology and healthcare development.

Author Contributions

Conceptualization, A.R. and Y.Y.; methodology, S.K.; validation, V.R., S.R; formal analysis, S.R.; data curation, S.K.; writing—original draft preparation, V.R., S.R; writing—review and editing, supervision, A.R.; project administration, A.R. All authors have read and agreed to the published version

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Conflicts of Interest

The authors declare no conflict of interest.

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