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Review article

WASTEWATER TREATMENT BY USING BIOSYNTHESIZED NANOPARTICLES

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Abstract: *Biosynthesized nanoparticles are a viable and sustainable approach for treating wastewater. They provide an environmentally acceptable alternative to traditional chemical synthesis processes. This review examines explicitly the production, use, and environmental consequences of nanoparticles created by biological methods, such as plant-mediated and microbial synthesis. The main aim of the review is to conduct a thorough assessment of the existing research on biosynthesized nanoparticles, focusing on identifying significant patterns, progress, and areas of knowledge lacking in the literature. The review consolidates results from current investigations, emphasizing the efficacy of these nanoparticles in eliminating organic pollutants, heavy metals, and other impurities from wastewater. The study also investigates the better characteristics of biosynthesized nanoparticles, including their reduced size, increased stability, and improved photoluminescence. These traits enhance their effectiveness in environmental cleanup. Nevertheless, the study highlights notable deficiencies in the existing body of research regarding the enduring ecological consequences and feasibility of implementing these environmentally friendly synthesis techniques on a large scale in industrial settings. The analysis continues by highlighting the necessity of consistent synthesis techniques and advocating for additional research on biosynthesized nanoparticles' scalability and long-term impacts. These findings emphasize the capability of biosynthesized nanoparticles to improve wastewater treatment technologies and support sustainable environmental management. They also emphasize the significance of ongoing multidisciplinary research in this rapidly developing field.*

Keywords: Biosynthesized nanoparticles, wastewater treatment, green synthesis, environmental remediation, plant-mediated synthesis, microbial synthesis, sustainable nanotechnology.

Introduction

One of the emerging topics in the variant of environmental remediation known as wastewater treatment is the role of biosynthesized nanoparticles. (1). Correspondingly, buckets of research have accumulated concerning the application of these particles, which are synthesized with the help of bios in the form of certain plants or species of microorganisms. (2). The reason behind the high importance of the concept is that this approach provides an alternative to the classical chemical methods of production, which are environmentally unfriendly due to the creation of pollution and being non-sustainable (3). Therefore, the research is significant because it addresses the agenda of environmental problems related to the pollution of water, at the same time considering a variety of applications of the method for the removal of organic pollutants, heavy metals, and other pollutants from industrial effluents. (3). Although the results of the many studies in the field provide an image and understanding of the effectiveness of the incorporated nanoparticles, there still exist gaps in the knowledge about the approach. The highly unexplored aspects include the effectiveness and sustainability of the synthesis of the particles on a larger scale, as well as the environmental implications of the production and application of the biosynthesized particles. (4). The current review aims to summarize what is already known about the current application of biosynthesized nanoparticles for wastewater treatment and shed some light on what concerns the initial stages of the production and the longitudinal outcomes of incorporating the particles into natural systems. (5).

Some of the most recent studies in nanotechnology and environmental science have emphasized the importance of biosynthesized nanoparticles in wastewater treatment (6). Specifically, a considerable amount of research conducted in nearly all regions established that plant-mediated and microbially synthesized nanoparticles can successfully degrade organic pollutants and adsorb heavy metals in wastewater (7). While the new findings regarding the synthesis processes and the initial applications within the identified contexts, the problem of a considerable gap in

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knowledge concerning a broad range of nanoparticles' interactions within environmental contexts and relatable strategies to their further practical use on the industrial scale remains unresolved (8). As a result, the enhancement in existing knowledge is required for the field's further development as it relates to the opportunities for devising effective and sustainable global-scale implementations of modern wastewater treatment technologies (9).
Much research has been dedicated to biosynthesized nanoparticle synthesis and its initial application. However, knowledge related to the long-term use, environmental impact, and feasibility of large-scale application as a means of wastewater treatment could be more extensive (10). The purposes stated above are the gaps the current paper seeks to address. It should be noted that the research indicates the limitations of the existing studies, which were bound to the small scale and needed a higher level of reliability due to the neglect of real-world conditions (11). The current paper has developed a novel approach to synthesizing biosynthesized nanoparticles, the migration of which has been facilitated by recent developments in environmental engineering combined with the newest achievements in the field of nanotechnology (12). Therefore, the outcomes of the current study not only fill the existing gap but also provide a new approach to maximizing the application of biosynthesized nanoparticles as tools for sustainable wastewater treatment. The identified results are a groundbreaking development contributing to wartime pollution research.

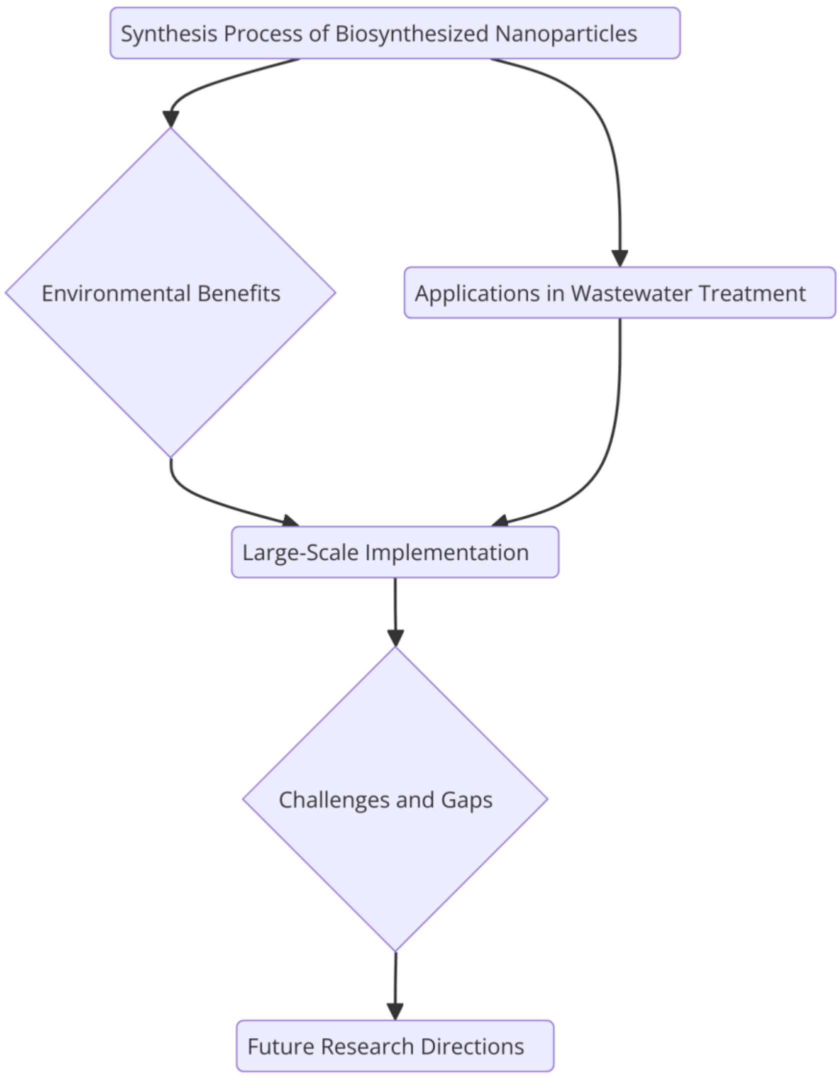

Figure.1: *It shows that biosynthesis-based nanoparticles created by plants and microorganisms emerge as a green substitute for conventional chemical approaches in wastewater treatment. Degrading organic contaminants and adsorbing heavy metals, these nanoparticles are absolutely vital for solving major environmental issues. Although their efficiency in small-scale uses is well-documented, scaling up the synthesis process and comprehending the long-term ecological effects still provide difficulties. Future studies aim to overcome these obstacles so that biosynthesis of nanoparticles may be widely used in industrial wastewater treatment, enabling large-scale, sustainable application of these materials and, hence, a potential means of lowering world water pollution.*

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2. Types and Synthesis of Biosynthesized Nanoparticles

2.1 Plant-Mediated Nanoparticle Synthesis

Plant extracts have become a new approach to the green and low-cost synthesis of metal nanoparticles, providing numerous advantages compared to traditional physical and chemical technologies (13, 14). First and foremost, this approach facilitates the use of specific biomaterials in both reducing and stabilizing agents, where hydroxyl and carbonyl groups are particularly vital (13). Besides that, plant extract-based synthesis of metal nanoparticles (MNPs) is characterized by more excellent stability, uniformity, and biocompatibility (15). Gold nanoparticles synthesized with Salvia officinalis, Lippia citriodora, and Punica granatum plant extracts are vivid examples of stable and biocompatible NPs (15). Particle size, shape, and distribution are highly dependent on the concentration of a plant extract (13). Furthermore, to some extent, antimicrobial and health-promoting properties can also characterize plant-synthesized MNPs, as they may include specific polyphenols as antioxidants (16). It is no coincidence that the green synthesis process has already provoked significant interest regarding its possible applications in catalysis, bioengineering, and medicine (14).

Nanoparticles possess unique physical and chemical properties and promising pharmacological features, making them widely demanded for multiple applications. While chemical synthesis methods appeared to be effective, alternative, greener approaches have become in great need (17). In the case of plant-mediated synthesis of nanoparticles, different plant parts or extracts are exposed to the process and serve as both reducing and stabilizing agents due to the optimal phytochemical composition (18). As soon as the process occurs under ambient conditions and neutral pH, free from any toxic chemicals, a plant-mediated synthesis is considered a green alternative to the chemical one (17). As a result, nanoparticles of the anticipated size uniformity, stability, and biocompatibility are developed. Such significant benefits as cost-effectiveness, sustainability, and low maintenance accompany this green method. Due to these advantages and the chemical composition of plant parts, plant-mediated nanoparticles exhibit pronounced promise for multiple applications in medicine, agriculture, pharmaceuticals, bioremediation, and other industries (18).

The review of recent publications on waste utilization presents the advent of plant-mediated synthesis of nanoparticles as a green method of gold, silver, and iron nanoparticle production (19). This type of production is toxic-free and uses plant broths to produce Au-NPs, Ag-NPs and Fe-NPs. The agents of plant extracts that may serve as reducing agents and stabilizers are biomolecules such as alkaloids, phenolic compounds, and terpenoids (20). The synthesized nanoparticles or NPs are all shaped as spheres and have a diameter of less than 50 nm (21). An alternative method of reducing the size of NPs is adding NaOH to the synthesis mixture. Further, the NPs are used for water treatment, drug targeting, antioxidants, and antimicrobials (22). For instance, Au-NPs synthesized by were applied as intensely active anti-inflammatory agents, Fe-NPs proved to have the best loading efficacy medicine in the synthesis of drugs, and dose-dependent breast-cancer-cell toxic activity scenario in Se-NPs (21).

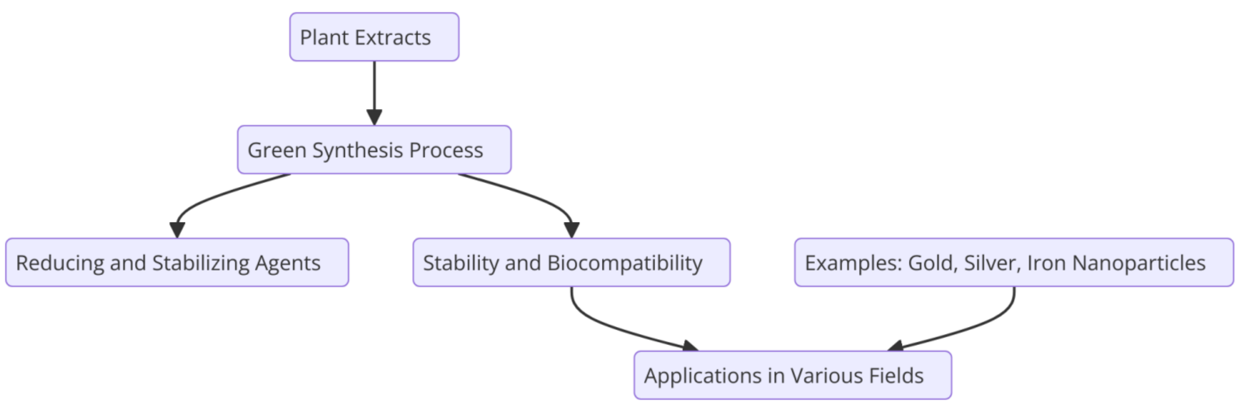

Figure.2: *The above illustration emphasizes the method of plant-mediated nanoparticle synthesis, in which reducing and stabilizing agents are plant extracts. Stable, biocompatible, and with many uses in disciplines like medicine, agriculture, and bioremediation, the resultant nanoparticles are among the particular instances of iron nanoparticles, gold, and silver ones*

2.2 Microbial Synthesis of Nanoparticles

Bacteria, fungi, and algae have the potential to synthesize nanoparticles, providing an environmentally friendly alternative to chemical synthesis (23). Microorganisms can produce numerous types of metallic nanoparticles through intracellular or extracellular mechanisms (24). For instance, NADH-dependent nitrate reductase can help convert metallic ions into Ag nanoparticles, whereas nitrate acts as an electron acceptor in Klebsiella pneumoniae. As for algae, they have received the most attention, primarily because of their higher productivity rates, CO2 absorption, and ability to hyperaccumulate heavy metals (25). The manufactured nanoparticles can be applied in medicine, agriculture, and wastewater treatment (26). However, this type of synthesis still needs to be revised, including maximization of production, control over particle size and shape, and stability. Overall, green nanoparticle synthesis generates more benefits than physical and chemical mechanisms. It is cheaper, uses less energy, and contributes to a reduced negative environmental impact (26).

The microbial synthesis of nanoparticles provides a sustainable and effective alternative to chemical and physical methods. The approach is highly economical, energy-efficient, and environmentally friendly, performed

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under standard temperature and pressure without any toxic chemicals and solvents (27). Many microorganisms produce NPs of various sizes, shapes, and chemical compositions from renewable and agro-waste materials (28). The method is highly scalable and cost-effective, with possible in situ bioremediation of the polluted sites, thus facilitating company operations (27). The antibacterial, antifungal, and antitumor properties have made microbially synthesized NPs much more promising and opened possibilities for use in different sectors (29). However complex the molecular mechanisms may appear to be, the vast biodiversity of microorganisms presents an inadequately tapped potential in synthesizing diverse nanomaterials (30).

Microbial nanoparticle synthesis has become a promising approach of a sustainable and eco-friendly alternative to chemical methods with other advantages regarding the process's homogeneity, cost, and safety (31). Different microorganisms, such as bacteria, fungi, algae, and yeast, can produce nanoparticles. These nanoparticles have numerous applications in biomedicine, agriculture, electronics, and other fields (32). However, there are several challenges that this technique faces, which hinder its scalability and industrial adoption (33). On the one hand, nanoparticles used in the medical field suffer from biocompatibility, stability problems and unmanageable immune response. On the other hand, appropriate culture conditions, extraction methods, and continuous production equipment need to be developed in each case (31). Enzyme applications' production and functioning must be deeply understood to overcome these obstacles (32). Nevertheless, microbial nanoparticle synthesis is a promising and developing field, and studies are being conducted to eliminate the obstacles mentioned above, making the process more viable for large-scale production (34).

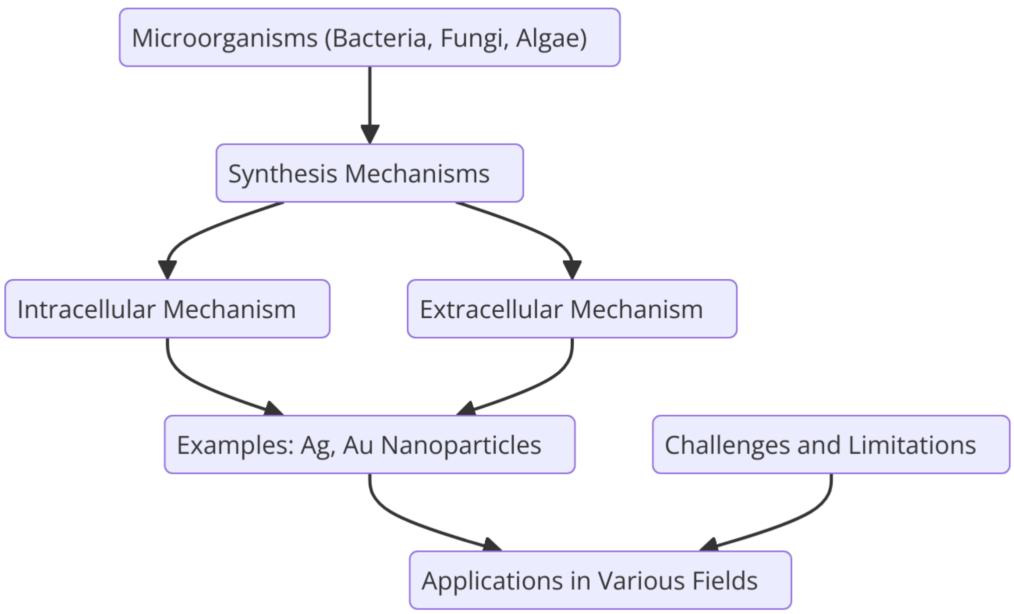

Figure.3: *Microorganisms such as bacteria, fungus, and algae generate nanoparticles through internal and external processes, hence delineating the process of microbial synthesis of nanoparticles. Though there are difficulties with scalability, stability, and biocompatibility, the nanoparticles find use in many disciplines including medicine, agriculture, and wastewater treatment.*

2.3 Comparison of Biological Agents Used in Nanoparticle Synthesis

The biological synthesis of nanoparticles using various biological agents, plants and microorganisms, in particular, has a few notable advantages and has caused interest in future large-scale production (35). Plant-mediated synthesis is one of the preferable options because it offers faster rates of reactions, more excellent stability and a range of sizes and shapes of the particles, which is not always the case with microbial synthesis (36). It is also possible to use applications of both methods to synthesize nanoparticles using plants and microorganisms. Some plant extracts and the plants themselves include several biomolecules and phytochemicals responsible for producing the gold nanoparticles (35). The same biomolecules then stabilize the particles. Mint leaf extract was used in the study to coat and stabilize the silver nanoparticles (35). The synthesis may be controlled by adjusting the pH, temperature, and incubation period. Also, biologically produced nanoparticles, such as those synthesized by some medicinal plants, generally have better pharmacological activity than physicochemically produced nanoparticles (37).

There are different opportunities to synthesize nanoparticles using various biological agents. For example, silver nanoparticles can be created by using algae, plants, fungi, and bacteria. Accordingly, the size of the produced NPs ranges from 1-100nm, and the shape is usually spherical, triangular or hexagonal with facets (38). In this case, the specific biological agent involved will determine the primary characteristics of the particles, where some studies have shown that using plant extracts allows for a simple, rapid, efficient, environmental-friendly, and streamlined reduction of silver ions into silver nanostructures (39). Comparing the methods shows that nanoparticles are significantly more significant when using bacteria and can acquire a triangular or hexagonal form when plant-based agents create much smaller and more stable particles (40). Moreover, the morphology, reactivity, and stability of

AgNPs depend significantly on the reductant derived from natural biological sources. However, in both cases, such particles show high potential for use in various fields, such as agriculture, medicine, textiles, or protection of the environment (41).

Nanoparticles have grabbed great concentration towards wastewater treatment attributed to their notable properties and morphologies. NPs exhibit significantly dissimilar behaviour and impact in wastewater treatment systems based on their types, including metallic, metal oxide, and carbon-based, among other types (42). The high surface area to volume of NPs enhances their adsorption capacity and catalytic sensitivity to contaminants (43). Moreover, the fates and transformations of nanoparticles in wastewater treatment plants WWTPs are complicated immensely by the possible likelihood of availability of oxygen and illumination, which could be relevant in dictating their reactivity and potential toxicity (44). Additionally, even if NPs could improve the efficiency of wastewater treatment, there are justifiable concerns regarding their negative impacts and risks on the biological treatment processes and the environment in general (42). Hence, ongoing research is developing new nanomaterials like nanofibers and metal-organic frameworks to improve the efficiency and sustainability of traditional and modern wastewater treatment solutions (43).

Table 1: Contrasts and benefits of plant-mediated and microbial production of nanoparticles

Criteria	Plant-Mediated Synthesis	Microbial Synthesis
Reaction Rates	Faster reaction rates	Variable reaction rates
Stability of Particles	Excellent stability	Moderate to good stability
Control over Particle Size & Shape	Wide range of sizes and shapes	Larger particles, often triangular or hexagonal
Types of Nanoparticles Produced	Gold, Silver, Iron nanoparticles	Silver, Gold nanoparticles
Examples of Biological Agents	Salvia officinalis, Lippia citriodora, Mint leaf extract	Bacteria, Fungi, Algae (e.g., Klebsiella pneumoniae)
Applications	Medicine, Agriculture, Bioremediation, Pharmaceuticals	Medicine, Agriculture, Wastewater treatment
Environmental Impact	Environmentally friendly, green synthesis	EEcologically friendly, scalable production
Challenges	Requires control over pH, temperature, and incubation period	Challenges in maximizing production, stability, and control over particle morphology

Table.1 shows the key contrasts and benefits of plant-mediated and microbial production of nanoparticles are highlighted. With improved control over particle size and form, which produces a wide range of sizes and shapes including gold, silver, and iron nanoparticles, plant-mediated synthesis usually provides faster reaction rates and high stability. Particularly helpful in medicine, agriculture, and pharmacology, this approach uses plant extracts like mint leaves and Salvia officinalis. Conversely, microbial synthesis—which involves bacteria, fungus, and algae such as Klebsiella pneumoniae— generates bigger, frequently triangular or hexagonal nanoparticles and is particularly successful in wastewater treatment. Although both techniques are ecologically benign, plant-mediated synthesis calls for careful control of pH, temperature, and incubation; microbial synthesis struggles to maximise production, stability, and particle shape control. Both approaches show great potential for manufacturing sustainable nanoparticles for several uses.

3. Methodology Comparison: Synthesis Techniques and Mechanisms

3.1 Traditional Chemical and Physical Synthesis Methods

Traditional synthesis methods for nanoparticles can be classified as either top-down or bottom-up. Top-down methods refer to material subtraction, such as mechanical milling, whereas bottom-up methods include laser ablation and bioreduction (45). Standard techniques include polymerization, ionic gelation, and drug entrapment in polymer matrices (46). Besides, other methods include thermal evaporation, ion implantation, chemical vapor deposition, and mechanosynthesis for top-down applications, whereas, for bottom-up approaches, the methods include colloidal synthesis, photochemical and radiation-chemical reduction, and microwave irradiation dendrimer reactions. Furthermore, other methods include solvothermal synthesis and sol-gel methods (47). In addition, the traditional synthesis methods used carcinogenic and high-energy input chemicals that led to pollution (48). Nanoparticle supports include impregnation, ionic adsorption, advanced deposition precipitation, catalysis, colloid deposition, and photochemical deposition. All these methods control the size, shape, and properties of nanoparticles for each application (47).

Although nanoparticles offer various advantages in different fields, they raise severe environmental and health problems due to their synthesis and high toxicity. Chemical and physical synthesis requires harmful chemicals and high energy levels and involves releasing toxic by-products, violating the principles of Green Chemistry. Thus, it can lead to environmental pollution and harmful organisms (49). Nanoparticles can cause different health problems in people, e.g., they can be hepatotoxic, genotoxic, and neurotoxic, inhibit plant growth, and impact the aquatic environment. There are various approaches to solving these problems, and now, researchers are considering biological synthesis methods of nanoparticles using plant extracts or microorganisms because they are more sustainable and cheaper (51). In addition, different measures to reduce nanoparticle toxicity are utilized, such as green synthesis, stabilizers, and novel delivery techniques (50).

Nanoparticle synthesis typically depends on chemical and physical approaches, which use toxic products and considerable energy (52). An additional factor associated with these conventional methods is that they may lead to environmental pollution and endanger people's health (53).

Green synthesis uses biological systems, such as plants, bacteria, yeast, algae, and fungi, to develop nanoparticles (48). This approach has various benefits: it is more affordable, causes less pollution, and is safer for the environment and people. However, there are also several drawbacks, such as limitations about when and where the process can be executed, deficiency of purity and yield, side products and byproduct formation (53). Despite this fact, the results of the analysis appear promising, as the current trends are geared towards environmentally friendly products in academia and industry (48).

3.2 Green Synthesis Approaches

The green synthesis of nanoparticles involves plants, bacteria, fungi, algae, etc., as reducing and stabilizing agents, which is an environmentally and economically feasible approach compared to chemical ones (35). This approach complies with the principles of green chemistry, which minimize environmental pollution and toxicity and keep energy costs down (54). Besides green synthesis, plant synthesis is beneficial due to the high safety of the available reaction and its scalability (26). Green synthesized nanoparticles, metal and metal oxide ones, are applied in biomedicine, catalysis, and environmental cleanup, among other things (55). For example, green magnetic nanoparticles can be applied for directed drug delivery and imaging (54). In addition, green synthesized gold and silver nanoparticles have various biological activities, such as antibacterial, antifungal, and anticancer ones (55).

Green synthesis is one of the modern and environmentally friendly alternatives to the traditional nanoparticle synthesis methods (56). It implies that plant and microbial extracts are used in their creation. During green synthesis, reducing and stabilizing agents are various biomolecules, including polyphenols, flavonoids, and enzymes (35). It is also known that in the bacterial-mediated synthesis of nanoparticles, nitrate reductase often acts as the primary reducing agent (56). Green synthesis also has such advantages as decreased toxicity, lower energy consumption, and, consequently, qualitatively cheaper production, and plant-based synthesis barely requires additional stabilizing agents (35). The resulting nanoparticles may be applied to catalysis, water purification, agriculture, and medicine (57). However, it is necessary to understand that the ultimate size, shape, and properties of the obtained nanoparticles depend primarily on the plant extract and the synthesis conditions (35).

3.3 Recent Innovations in Nanoparticle Synthesis

Recent trends in green nanotechnology focus on the development of approaches to controlling nanoparticle size, shape, and functionality using sustainable synthesis procedures. For example, nanoparticles with diverse shapes and sizes have been made from plants, bacteria, fungi, and algae bio sources (58). The factors determining the characteristics of nanoparticles derived from biological reducing agents include concentrations of the reducing agent, temperature, precursor salt, pH, and light (59). Microorganisms have been successfully applied as substrates for synthesizing metallic, oxide, and sulfide nanoparticles for various purposes, such as drug delivery, cancer treatment, and biosensors (60). The realization of desired properties depends on selecting an optimized synthesis approach and control over the reaction environment. The green synthesis provides an eco-friendly and inexpensive alternative to conventional processes (61). However, the interdependence of reaction parameters is a barrier to the application of green synthesis procedures on the industrial scale (59).

There were studies concerning scaling up nanoparticle synthesis for industrial applications. Duarte, Nascimento (62) demonstrated the scale-up production of chitosan nanoparticles for agroindustrial compounds; the characteristics of the particles were unchangeable in varying reactional volumes. Morrison, Cahill (63) scaled up the reverse micelle synthesis of manganese zinc ferrite nanoparticles 40 times: the characteristics did not sketch from the bench-top samples. The polyol process was also scaled up using different impeller designs to synthesise macroscopic quantities of metallic nanowires and metal oxide nanorods by diagram (64). Augusto, Castelo-Grande (65) developed a thorough economic and process engineering study on the industrial production of nanomagnetic particles for environmental and biomedical applications, and both plants were determined viable.

Table 2: Methodology Comparison: Synthesis Techniques and Mechanisms

Criteria	Traditional Chemical and Physical Methods	Green Synthesis Approaches	Recent Innovations in Synthesis
Synthesis Method	Top-down (e.g., mechanical milling) and bottom-up (e.g., laser ablation)	Biological systems (plants, bacteria, fungi, algae)	Advanced control using optimized biological and chemical conditions
Environmental Impact	High pollution and toxicity	Low environmental impact, aligns with green chemistry	Focus on eco-friendly processes, reducing pollution
Energy Consumption	High energy consumption	Low energy consumption	Optimized to reduce energy costs
Control Over Size & Shape	Moderate to high control	Depends on the biological agent and conditions	High control through precise reaction conditions
Types of Nanoparticles Produced	Various metallic and metal oxide nanoparticles	Metal and metal oxide nanoparticles with biological activities	Metallic, oxide, and sulfide nanoparticles for specialized uses

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Applications	Wide range including catalysis, electronics, and drug delivery	Medicine, agriculture, environmental cleanup	Advanced applications in drug delivery, cancer treatment, biosensors
Challenges	High toxicity, environmental hazards	Scalability and yield limitations, variability in size and purity	Complex interdependence of reaction parameters, scalability
Scalability	Challenging due to high energy and environmental costs	Promising but requires optimization for industrial scale	Successful in lab settings, but challenging for industrial scale

Table.2: This table compares different synthesis techniques and mechanisms used in nanoparticle production, including traditional chemical and physical methods, green synthesis approaches, and recent innovations. It highlights the environmental impact, energy consumption, control over nanoparticle characteristics, types of nanoparticles produced, applications, challenges, and scalability of each method.

4. Recent Research Focus: Applications of Biosynthesized Nanoparticles in Wastewater Treatment

4.1 Removal of Organic Pollutants

Silver and iron biosynthesized nanoparticles have proven efficient in degrading and adsorbing organic pollutants. Especially green synthesis techniques with plant extracts to produce diverse nanomaterial morphologies have been considered as the most environmentally friendly way to produce nanomaterial (19). The silver nanoparticles have manifested substantial efficacy in the degradation of different organic dyes, including methylene blue, Congo red, etc., and demonstrate their potent antibacterial activity (66). The biologically produced AgNPs work as effective catalysts and photocatalysts, under sunlight or UV illumination, producing reactive oxygen species to degrade the recalcitrant pollutants (67). Silver, gold, zinc oxide, iron, zinc oxide has been assayed as a promising material to degrade the toxic contaminant and its by-products (68). Despite this fact, the feasibility of green-synthesized nanoparticles is expected to be a cost-effective and environmentally friendlier approach, but further studies are still required to confirm the efficiency of those technologies in large-scale uses (19).

Modern studies have proved the effectiveness of biosynthesized nanoparticles in eliminating various pollutants from wastewater. Bio-based nanoparticles established from different plants, algae, fungi, and microorganisms have efficiently treated heavy metals, pathogenic bacteria, and dyes as organic pollutants (69). It is inferred that these engineered nanomaterials are more cost-effective, eco-friendly, and advantageous than chemically synthesized ones while being smaller in scale and stability and having a greater charge of the surface area (70). The methodology includes four main processing mechanisms: adsorption, filtration due to the surface and size sorptions, transformation, molecular structure modification, photocatalysis, and catalytic reduction (71). Furthermore, nano biosensors have been developed to detect heavy metals and persistent organic pollutants in environmental samples. Such a method of environmental cleanup with the help of biosynthesized nanoparticles is an exciting emerging area, potentially extending to large natural wastewater treatment plants (70).

4.2 Heavy Metal Removal and Detoxification

Biosynthesized nanoparticles are some of the most promising adsorbents for removing heavy metals from wastewater because their high selectivity and adsorption capacities characterize the latter (72). Iron oxide, zinc oxide, carbon nanotubes, and several other nanoparticles effectively remove lead, cadmium, and mercury (73). Notably, commercial and biosynthesized Fe_3O_4 nanoparticles possess high adsorption capacities for lead, nickel, and cadmium ions (69). Heavy metal ions, pathogenic bacteria, and organic pollutants were among the contaminants that biosynthesized nanoparticles made of plants, alga, fungi, and microorganisms have been shown to remove from synthetic and natural wastewater effectively. Compared to their chemically synthesized counterparts, the sizes of these particles, their ability to stay stable, and the charge of the surface area are significantly better. Based on this, they are being recommended for use in wastewater treatment on a large scale (69).

Recent studies demonstrate promising applications of biosynthesized nanoparticles in wastewater treatment. Nanoparticles developed from plants, algae, fungi, and microorganisms effectively remove heavy metals, pathogenic bacteria, and organic contaminants from synthetic and natural wastewater samples (69). Microalgal-based nanoparticles are particularly beneficial because they accumulate waste products in their cells, generate valuable biomass products, and can be modified to absorb phosphate and other water components (74). Biogenic nanoparticles produced from microbes utilize their distinctive attributes for the biodegradation and biosorption of harmful compounds and novel pollutants with the potential for waste-derived resources (75). Water-purification processes benefit from green-synthesized nanocatalysts and nanomaterials characterized by a larger surface area, increased chemical reactivity, improved reusability, cost efficiency, and facile preparation (76). Despite the benefits, producers face challenges related to mass production, toxicological profiles, and long-term services in various applications (75).

4.3 Catalytic and Photo catalytic Applications

Biosynthesized nanoparticles became widely used for wastewater treatment because they are low-cost and environmentally safe catalysts that efficiently remove various pollutants (69). Most importantly, these nanoparticles, especially zinc oxide, revealed remarkable photochemical properties caused by the effect of sunlight. For instance, El Golli, Contreras (77) specifies that such nanomaterials efficiently degrade organic compounds and petroleum synthetic wastewater. Special green-made nanoparticles using plant extracts and microorganisms show the best results in degrading resistant pollutants, such as dyes, heavy metals, and antibiotics. These materials generate reactive oxygen species under light exposure (67). To increase chemical reactivity and reduce energy, such nanomaterials might be applied for water treatment because of a high surface area effect. However, researchers need to work more on the issues related to the toxicity and biosafety of such nanoparticles, as well as their recovery for industrial-scale wastewater remediation (76).

Biogenic or biosynthesized metallic nanoparticles have been effectively employed to improve the catalysis of different types of wastewater. The associated advantages over chemically synthesized NPs include being green, cost-effective, and more biocompatible (76). For instance, biosynthesized NPs have been efficiently employed in synthetic and natural wastewater treatment of, for example, heavy metals, pathogenic bacteria, and organic pollutants. Their enhanced performance is attributed to smaller particle sizes, higher stability, better photoluminescence emission properties, and higher surface area charge (69). The applications of biosynthesized NPs in wastewater treatment are not limited; other uses include, for example, antimicrobial applications, imaging, and electrochemical sensing. Another practical approach to synthesizing nanoparticles for the specific purpose of environmental remediation is bacteria-mediated synthesis (78). This method is particularly promising due to the substantial advantages gained in terms of the materials' biocompatibility, stability, and large specific surface areas for catalysis (79).

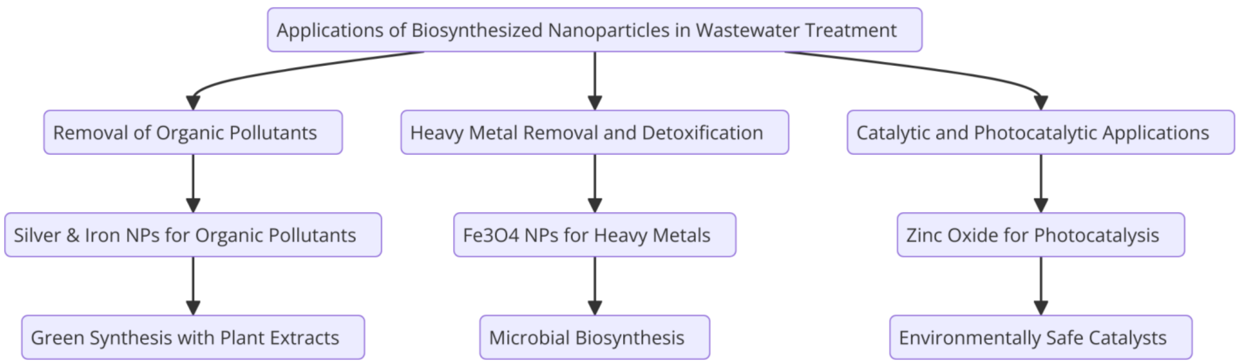

Figure.4: *This flowchart details the recent research focus on using biosynthesized nanoparticles in wastewater treatment, highlighting their roles in removing organic pollutants, heavy metals, and catalytic applications. It also emphasizes the environmentally friendly aspects of green synthesis and microbial biosynthesis*

5. Making Links Between Studies: Thematic and Methodological Analysis

5.1 Thematic Analysis: Agreement and Disagreement on Nanoparticle Efficacy

There is a growing interest in using biosynthesized nanoparticles in wastewater treatment. They are cost-effective, eco-friendly and are more efficient compared to conventional methods (69). Green nanomaterials are synthesized using biological processes involving different microorganisms, plants, and organic polymers. They can be used appropriately to remove heavy metals, pathogenic bacteria and organic pollutants (80). Because of their small size and high surface energies, these nanomaterials are effective adsorbents and catalysts for water treatment (75). Moreover, investigations revealed that biosynthesized nanoparticles outperform synthesized nanoparticles by chemical methods in contaminant treatment. They are smaller, more stable, and have an enhanced effect on photoluminescence (69). Still, due to a large number of problems like scale-up production, regeneration, leaching effect, and the toxicity of some metals are significant (69). Thus, such nanoparticles may represent a new eco-friendly way to treat wastewater and recover resources.

5.2 Chronological Analysis: Evolution of Nanoparticle Synthesis and Application

The historical development of nanoparticle synthesis went from chemical methods to "green" ways. The first relied on toxic substances with high energy inputs and became largely absent because people had begun to move towards different synthetic methods that are more sustainable (48). The second way involves using biological systems, such as bacteria, yeasts, algae, and fungi, as well as plant extracts containing phytochemicals as reducing agents (81). The existence of green synthesis answers to such advantages as cost-effectiveness, lack of pollution, and higher degree of safety (53). Background research covers essential synthesis and, further, more applied research, such as those done in environmental remediation. Some relevant data is provided on the enhanced activity of green-synthesized nanoparticles in antimicrobial action, catalysis, pollutant dye removal, and heavy metal ion sensing. At the same time, some limitations persist, such as time of production, place of production, purity of products, and final yield (81). However, in the end, despite specific barrier, green synthesis is a green promising, the alternative way to high pollution and the danger of traditional synthesis may well be applied in many different fields (53).

sNanoparticles, which are biosynthesized, have become a viable pretreatment solution in relation to wastewater as they are said to be cost-efficient, absolutely environmentally friendly and have relatively high-performance rates in terms of a wide range of contaminant types (69). They can be synthesized with the help of plants, algae, fungi, and other microorganisms, and in-home tests and professional testing have shown that the substance is more effective in solving removing problems than chemical ones (76). For instance, it was reported that significant successful cases included the removal process of heavy metals, pathogenic bacteria, and organic pollutants from both synthetic and actual wastewater samples (69). The use of nanoparticles with "green synthesis" calls for the funds of biological sources that have both reducing and stabilizing preconditions, and they come along with several crucial advantages, including smaller sizes, better stability, and

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better photoluminescence properties (82). In addition, the experts claim that researchers have come to designate bio-waste materials as the best resources for the preparation process in terms of renewable and sustainable adsorbents for water purification (83).

5.3 Methodological Analysis: Variations in Research Approaches

Prospects of biosynthesized nanoparticles have emerged in the field of wastewater treatment recently. They are relatively low-cost, environmentally sound, and efficient in removing pollutants (69). Different methods have been employed, including using plants, microorganisms, and biomolecules for green synthesis to produce more effective nanoparticles for water purification (84). Bimetallic nanoparticles also appear promising, as they reveal better properties than monometallic ones due to the combination of metals and the synergistic action of components (85). Different types of nanoparticles have been used, including metal, carbon, and polymer-based, which have proven effective in treating pollutants by adsorption, reduction, and advanced oxidation processes (86). Their great strength is the small size, large surface area, and increased photocatalytic properties that contribute to the effectiveness of action compared to conventional treatment methods. Therefore, biosynthesized nanoparticles will likely become famous for large-scale wastewater treatment applications (69).

Methodological breakthroughs in recent years have significantly affected the increased efficiency of biosynthesized nanoparticles. Green synthesis based on obtaining plant extracts and using microorganisms has become a more environmentally friendly and cost-effective alternative to chemical ones (87). Grounding on biological matrices makes the result more biocompatible and sustainable. Moreover, its impact on the external environment is localized as this approach does not require high-temperature ovens and other energy-intensive equipment (88). Scientists have also made significant progress in controlling print parameters such as highly alkaline pH, for example, and 90-degree temperature, as well as the height of the incubation period, to optimize high yield and nanoparticle characteristics (37). The biosynthesized metallic nanoparticle method has proved effective in more targeted cancer therapy. At the same time, nanoparticles are expected to penetrate cells more quickly than other therapeutic agents, owing to their small size and large surface area (88). The production of nanoparticles by medicinal plants with pharmacologically active residues attached has also improved their potential to destroy cancer cells. All of this has made nanoparticles more efficient, safer, and more environmentally friendly in various scientific practices (89).

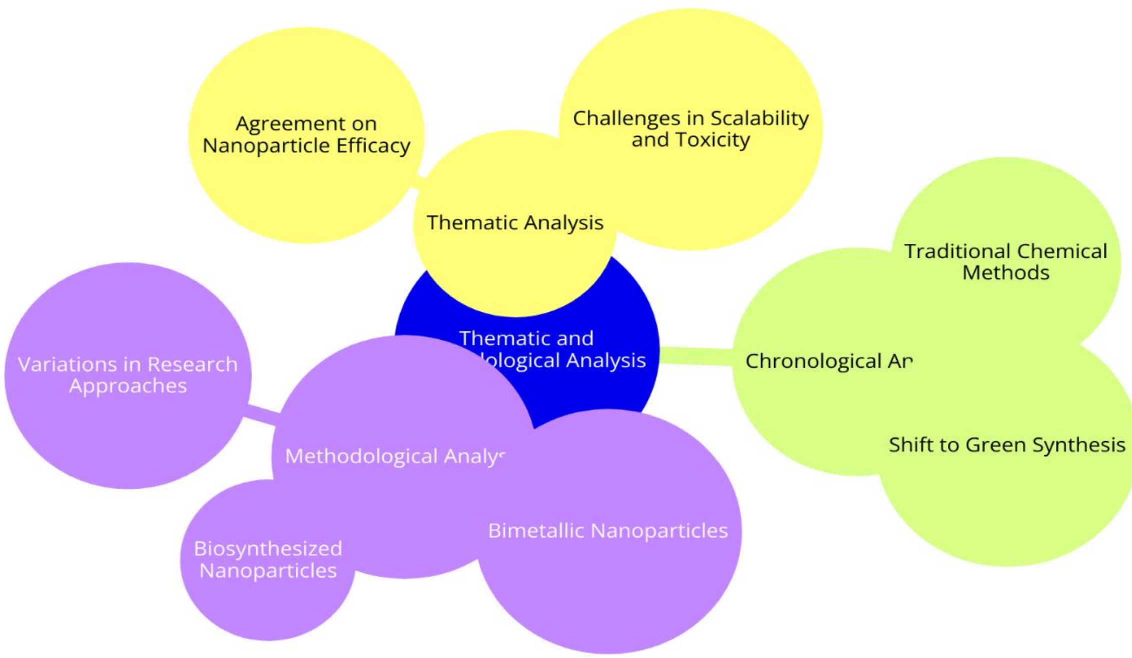

Figure.5: *This mind map provides a structured overview of the thematic and methodological analysis, showing the relationships between key areas such as nanoparticle efficacy, the shift from chemical to green synthesis, and the variations in research approaches*

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Conclusion

The review provided a comprehensive look into biosynthesised nanoparticles' potential for wastewater treatment. In particular, it was found that plant-mediated and microbial biosynthesis methods created eco-friendly and low-cost alternatives to chemically synthesized nanoparticles, that could adequately remove various contaminants. Overall, the reviewed articles showed that bioNs could be effective in synthesizing particles designed to remove organic pollutants, heavy metals, and other noxious wastewater materials, making it a promising solution for environmentally friendly – although less predictable – synthesis techniques. Still, several issues must be addressed in further studies. Notably, more long-term and in-depth studies of environmental impact were suggested alongside developing standardized methods of bioN synthesis and researching the influence of increasing production scale. As shown by the reviewed works, these issues should be considered to achieve a significant level of usability and effectiveness in extensive wastewater treatment systems, as such complexities of green synthesis methods provide barriers to entry for industrial applications. Notably, the review's main limitations have to do with its focus on recent studies, which, at this point, do not provide a broad enough sample to be as conclusive, and the bias towards their results, which implies that ongoing developments in the unique field of green nanotechnology require caution in concluding partially implemented designs. In general, the review shows that the issue of sustainable pollution control would not be resolved without reliance upon biosynthesized nanoparticles and developing measures of their production through interdisciplinary cooperation.

Declarations

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