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Review Article:
pros and cons of nanomaterials green synthesis

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Abstract:

Nanomaterials have found widespread applications in various scientific fields, including engineering, medicine, energy, and environmental science. Conventional methods of nanoparticle synthesis -such as chemical and physical techniques- are often costly, energy-intensive, and pose environmental and health hazards. In contrast, green synthesis provides an eco-friendly alternative, utilizing natural sources such as plants, bacteria, fungi, and agricultural waste to produce nanoparticles. These approaches significantly reduce the carbon footprint and environmental risks associated with traditional processes. Green-synthesized nanoparticles exhibit enhanced properties such as high catalytic activity, thermal and electrical conductivity, and biocompatibility, making them attractive for use in energy storage, optics, biomedical applications, cancer therapy, and catalysis. This review indicate to green synthesis of various types of nanomaterials - metal oxide-based, inert metal-based, carbon-based, and composites. Additionally, it discusses their potential industrial applications and the key factors influencing environmentally friendly nanoparticle production.

Key Words: Nanoparticles, Green synthesis, Green , synthesis , Nanotechnology.

مراجعة مقال:
طرق تحضير مواد نانوية في بيئة نظيفة

ميادة صبري ، كوثر أياد عبيد ، رشا أحمد هاشم
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مستخلص:

تُستخدم المواد النانوية على نطاق واسع في مختلف المجالات العلمية، بما في ذلك الهندسة والطب والطاقة وعلوم البيئة. غالبًا ما تكون الطرق التقليدية لتصنيع الجسيمات النانوية – مثل التقنيات الكيميائية والفيزيائية – مكلفة وتستهلك كميات كبيرة من الطاقة، وتُشكل مخاطر بيئية وصحية. في المقابل، يُوفر التصنيع الأخضر بديلاً صديقًا للبيئة، حيث يستخدم مصادر طبيعية كالنباتات والبكتيريا والفطريات والنفايات الزراعية لإنتاج الجسيمات النانوية. تُقلل هذه الأساليب بشكل كبير من البصمة الكربونية والمخاطر البيئية المرتبطة بالعمليات التقليدية. تتميز الجسيمات النانوية المُصنّعة بيئيًا بخصائص مُحسّنة، مثل النشاط التحفيزي العالي، والتوصيل الحراري والكهربائي، والتوافق الحيوي، مما يجعلها مرغوبة للاستخدام في تخزين الطاقة، والبصريات، والتطبيقات الطبية الحيوية، وعلاج السرطان، والتحفيز الكيميائي.

تشير هذه المقالة الى التطورات الحديثة في مجال التخليق النظيف لأنواع مختلفة من المواد النانوية – القائمة على أكسيد المعادن، والقائمة على المعادن الخاملة، والقائمة على الكربون، والمركبات. كما يناقش تطبيقاتها الصناعية المحتملة والعوامل الرئيسية المؤثرة على إنتاج الجسيمات النانوية الصديقة للبيئة.

الكلمات المفتاحية: الجسيمات النانوية، التخليق الأخضر، الطرق النظيفة، السلامة البيئية، تقنية النانو.

1. Introduction

Nanomaterials are defined as materials that possess at least one dimension within the nanoscale range of 1–100 nanometers. Due to their extremely small size and large surface area-to-volume ratio, these materials exhibit unique physical, chemical, and biological properties (1). Nanomaterials can exist in various morphologies, including nanoparticles, nanotubes, and nanowires, and can be composed of metals, metal oxides, polymers, ceramics, and carbon-based substances.

One of the key features of nanomaterials is the phenomenon of quantum confinement, which affects the movement of electrons and alters the overall behavior of the materials. This leads to distinct optical, electrical, and catalytic properties. As a result, nanomaterials have found applications in a wide range of fields such as electronics, energy storage, targeted drug and gene delivery, cancer therapy, biosensing, environmental remediation, imaging, diagnostics, and cosmetics (2,3).

There are two principal strategies for synthesizing nanoparticles: the top-down and bottom-up approaches (4). The top-down approach involves the physical or chemical breakdown of bulk materials into nanoparticles—examples include mechanical milling, laser ablation, and chemical etching. Although this method enables the production of nanoparticles on a large scale, it often lacks control over particle size, morphology, and purity(5).

In contrast, the bottom-up approach involves the chemical assembly of atoms or molecules into nanoscale structures. This method offers high precision in controlling nanoparticle characteristics and includes techniques such as sol-gel synthesis, hydrothermal methods, and chemical vapor deposition (6).

Green synthesis—also referred to as biological synthesis—emerges as a sustainable, cost-effective approach . It relies on ecofriendly conditions, such as mild temperatures, In addition, the review includes to evaluate the feasibility and advantages of employing green methods for nanoparticle synthesis and to highlight their growing importance in sustainable nanotechnology pressures, and pH, to fabricate nanoparticles without the need for toxic chemicals making it a promising option for environment-friendliness nanomaterial production (7).

2 .Synthesis of Nanoparticles from Various Sources in a Green Environment

green synthesis methods offer several advantages over conventional chemical approaches, particularly in terms of sustainability, safety, and environmental impact (8). These eco-friendly techniques are suitable for large-scale production, as they are non-toxic, energy-efficient, and capable of yielding nanoparticles with diverse sizes and morphologies tailored for specific applications.

A variety of plant parts leaves, stems, flowers, roots, and seeds—have been successfully utilized in the green synthesis of nanoparticles. In these processes, plant extracts serve dual acting both as reducing agents that convert metal ions into nanoparticles and as capping agents that stabilize the resulting structures (9). Many plant species are capable of reducing and stabilizing metal and metal oxide nanoparticles efficiently through their phytochemicals.

Numerous studies have confirmed the effectiveness of biosynthesis in producing a wide range of nanomaterials, such as silver, gold, zinc oxide, and titanium dioxide nanoparticles (10).

3 .Biological Elements and Preparation Techniques

Among the most promising clean and sustainable approaches to nanoparticle synthesis are biologically mediated techniques, which include plant-based synthesis, microbial synthesis, and enzymatic methods (11). These strategies are cost-effective, environmentally friendly, and typically conducted under mild conditions (12).

3.1 Plant-Mediated Synthesis

Plants offer a rich source of bioactive compounds such as flavonoids, alkaloids, terpenoids, proteins, and vitamins, which can effectively reduce metal ions and stabilize nanoparticles. This method—often referred to as phytonanotechnology—utilizes various plant parts, including roots, stems, leaves, and seeds, to synthesize nanoparticles (7). The choice of plant material depends on the desired properties of the nanoparticles, as different biomolecules influence size, shape, and stability . Examples of techniques for synthesizing plant-based nanomaterials include the following:

1 .Plant Extract-Based Silver Nanoparticles (AgNPs)

• Source: Plant extracts such as lemon, eucalyptus, orange peel, tea leaves, and aloe vera.

• Method: Silver nitrate ($AgNO_3$) is combined with plant extracts, and the presence of reducing agents such polyphenols and flavonoids in the plant extract causes the reduction of silver ions into silver nanoparticles (AgNPs).

To create silver nanoparticles, the green synthesis method merely boils or mixes the plant extract with a solution of silver nitrate. • Uses include sensors, wound dressings, and antimicrobial agents(13).

2 .Plant-Extracted Gold Nanoparticles (AuNPs) • Source: Plants such as pomegranates, green tea, ginkgo biloba, and Azadirachta indica. • Method: In a standard green synthesis procedure, gold chloride ($HAuCl_4$) is reduced to gold nanoparticles (AuNPs) by plant extracts that contain antioxidants such polyphenols. The plant extract offers stabilizers as well as lowering agents.

• Uses include biosensing, bioimaging, and drug delivery systems(14).

3 .Plant Extract-Based Zinc Oxide (ZnO) Nanoparticles

• Source: Leaf extracts from Bacopa monnieri, Coriander, and Moringa oleifera.

• Method: Plant extracts containing flavonoids and other phytochemicals that can reduce the zinc ions to generate zinc oxide nanoparticles are combined with zinc salts (such as zinc acetate or zinc nitrate). The procedure can be carried out in mild weather or at room temperature.

• Uses include photodetectors, antimicrobial coatings, and cosmetics(15).

4 .Plant Extract-Based Copper Oxide Nanoparticles (CuO NPs)

• Source: Plant extracts, including those from Mentha piperita (peppermint) and Cinnamomum verum (cinnamon).

• Method: Copper ions are reduced to copper oxide nanoparticles (CuO) by a reaction between copper sulfate ($CuSO_4$) and plant extracts. This reducing procedure is brought about by the antioxidants in the plant extracts.

• Uses include agricultural applications, antibacterial agents, and catalysts(16).

5 .Plant Extract-Based Titanium Dioxide (TiO_2) Nanoparticles

• Source: Plant extracts, including

sage and coriander.

• Method: Titanium salts, such as titanium tetrachloride or titanium sulfate, are reduced into titanium dioxide nanoparticles using plant extracts and their inherent reducing agents. High-energy procedures and hazardous chemicals are avoided in the green synthesis approach.

• Uses include sunscreen, water filtration, and photocatalysis(17).

6 .Plant Extract-Based Magnesium Nanoparticles

• Source: Pineapple, pepper, and citrus fruit extracts.

• Method: Plant extracts containing polyphenols and other reducing agents decrease magnesium ions, such as magnesium chloride. In mild conditions, this environmentally friendly process aids in the production of magnesium nanoparticles.

•Uses include batteries, catalysts, and energy storage (18).

7 .Plant Extract-Based Carbon Nanoparticles (CNPs) or Carbon Quantum Dots (CQDs)

• Source: Plant products high in carbon, including coffee grounds, banana peels, orange peels, and tomatoes.

• Method: Pyrolysis, which involves heating plant material without oxygen, or hydrothermal carbonization, which uses high-pressure water, are two methods for creating carbon nanoparticles(19). These techniques yield extremely useful nanoparticles and are sustainable.

• Uses: Fluorescent probes for environmental monitoring, medication delivery, and Bioimaging(20).

8 .Plant Extract-Based Magnetic Nanoparticles (FeO_4)

• Source: Plant extracts, like those found in mint or tamarind.

• Method: In the presence of plant extracts, iron ions (such as ferric chloride) are reduced to produce iron oxide nanoparticles (FeO_4)(21). These particles are frequently employed in environmental and medicinal applications due to their magnetic characteristics.

• Uses include biosensors, wastewater treatment, and magnetic resonance imaging (MRI.(23)(22))

9 .Chitosan Nanoparticles from Plant-based Chitin: The first source of chitosan nanoparticles is fungal or crustacean chitin, even if green production uses plant-based resources like Moringa seeds.

• Method: Chitin that has been extracted from plant sources is used to create chitosan nanoparticles. They can be altered for a variety of purposes and are employed as biopolymers.

• Uses include wound care, food packaging, and drug administration.

Benefits of Synthesising Nanomaterials from Plants:

* Eco-friendly: Steers clear of hazardous chemicals and makes use of renewable resources.

*Economical: Minimizes the need for costly chemicals and energy-intensive procedures.

*Biocompatibility: The materials can be used in medical applications since they are frequently more compatible with biological systems.

*Sustainability: Lessens the impact on the environment than traditional synthetic Techniques (24).

3.2 Microbial Synthesis

Microorganisms such as bacteria, fungi, and yeasts are capable of producing nanoparticles intracellularly or extracellularly through enzymatic and metabolic processes. These organisms act as "nano-factories" due to their high yield, ease of cultivation, and minimal growth requirements. For example, silver nanoparticles have been synthesized using *Bacillus licheniformis* and *Klebsiella pneumoniae*, while *Morganella psychrotolerans* has been employed to Produce titanium dioxide nanoparticles(25). Microbially synthesized nanoparticles are often more uniform, and the process is relatively simple to scale. However, challenges such as purification and contamination must be addressed for industrial applications.

3.3 Enzymatic and Biomolecule-Assisted Synthesis

Biological molecules—including proteins, sugars, and enzymes—play a crucial role in nanoparticle synthesis by influencing their formation, growth kinetics, and final properties. Enzymes, in particular, help control the size and morphology of nanoparticles while minimizing the need for harsh conditions or toxic solvents (26,27). Additionally, these biomolecules can enhance the antimicrobial and biomedical potential of the synthesized nanoparticles by stabilizing their surfaces and preventing aggregation.

.1 Pharmaceutical Enzymatic Synthesis: An Example Synthesis of Penicillin Enzymes are used in biotechnological procedures to produce penicillin, one of the earliest antibiotics(28). The enzyme penicillin acylase catalyzes the breakage and reformation of the penicillin molecule, resulting in the synthesis of penicillin G. Because of the process's high level of selectivity, the intended antibiotic is produced with little adverse effects(29).

2 .The Production of Biodiesel via Enzymatic Catalysis

As an illustration: The process of transesterifying fats and oils Lipase enzymes can catalyze the conversion of triglycerides (fats and oils) to biodiesel (fatty acid methyl esters). These enzymes produce glycerol and biodiesel by gently and non-toxically breaking down the triglyceride molecules. This is thought to be a more environmentally friendly option than conventional chemical catalysts(30).

3 .Biomolecule-Assisted Nanoparticle Synthesis: Green Synthesis of Silver Nanoparticles, for instance The method of creating silver nanoparticles using plant extracts, enzymes, or other biomolecules is referred to as "green synthesis." For instance, silver ions (Ag^+) can be reduced to silver nanoparticles (AgNPs) using plant extracts or Corynebacterium species. This technique offers control over the size and structure of nanoparticles and is environmentally safe(31).

4 .Enzyme-Driven Polymerization: An Illustration Polylactic Acid (PLA) Synthesis Mediated by Enzymes Lactic acid can be polymerized enzymatically to create polylactic acid, a biodegradable material. Lactic acid can be converted into lactate with the help of the enzyme lactate dehydrogenase. Lactate can then be polymerized into PLA, a substance frequently used in eco-friendly packaging(32).

5 .Synthesis of Chiral Compounds Catalyzed by Biomolecules: An Example of Asymmetric Synthesis of Chiral Drugs Chiral chemicals can be synthesized asymmetrically using enzymes like lipases and aminotransferases. The enzymatic synthesis of chiral amines, which are essential intermediates in medications ike antihistamines and antidepressants, is one prominent example.

Enzyme-Assisted Biofuel Synthesis: An Illustration Hydrolysis of Cellulose Mediated by Cellulase Cellulose is broken down by the enzyme cellulase into glucose, which can subsequently ferment to create bioethanol, a renewable biofuel. An integral part of turning plant biomass into biofuels is this enzymatic process

These illustrations demonstrate how biomolecule-assisted synthesis and enzymatic synthesis can offer more efficient, sustainable, and selective routes for the synthesis of different chemicals(33).

4 .Nanomaterials Based on Metals and Metal Oxides

Metal and metal oxide nanoparticles have attracted significant interest in various scientific and industrial fields due to their unique physical, chemical, and biological properties. Their nanoscale form enhances attributes such as surface reactivity (refers to a material's surface's capacity to interact with other molecules or substances, frequently resulting in chemical reactions. It is essential for figuring out how nanoparticles—including those made by microbes—behave in different settings and applications) conductivity, and catalytic efficiency, making them suitable for applications in medicine, energy, electronics, and environmental remediation (34).

4.1 Metal Oxide Nanoparticles

Nanoparticles derived from metal oxides—such as zinc oxide (ZnO), titanium dioxide (TiO_2), and iron oxide (Fe_3O_4)—are widely used because of their biocompatibility, optical properties, and antimicrobial effects. The green synthesis of these particles has gained momentum due to its low cost and eco-friendliness. Plant extracts, microorganisms, and other biological systems have been successfully employed to synthesize these oxides under ambient conditions, producing nanoparticles suitable for photocatalysis, drug delivery, and antibacterial applications (35).

4.2 Noble (Inert) Metal Nanoparticles

Noble metals such as gold (Au), silver (Ag), platinum (Pt), palladium (Pd), and rhodium (Rh) are commonly used in green synthesis due to their ease of reduction, even with mild biological agents (36). These nanoparticles are highly valued for their stability, surface plasmon resonance, and high catalytic activity. As a result, they are widely applied in fields ranging from electronics and sensing to medicine and energy storage.

Green synthesis methods offer a reliable and environmentally safe route for producing noble metal nanoparticles, often resulting in enhanced bioactivity and compatibility compared to those made by conventional chemical methods.

5 .Limitations and Factors Influencing Clean Preparation

Despite the numerous benefits of clean and green synthesis methods, several limitations and influencing factors must be considered to optimize nanoparticle production and scalability.

5.1 Variability in Raw Materials

One of the major challenges in green synthesis is the variability in the composition and quality of natural precursors such as plant extracts or microbial cultures. Since these biological materials can vary depending on geographic origin, cultivation conditions, and seasonal changes, the reproducibility and consistency of nanoparticle synthesis may be affected (37).

5.2 Scalability and Standardization

While green synthesis is effective on a laboratory scale, transitioning to large-scale production poses difficulties. Controlling parameters such as pH, temperature, and concentration of bioactive compounds can be complex. Additionally, the lack of standardized protocols for biosynthesis limits its industrial implementation (38).

5.3 Purity and Characterization

Nanoparticles synthesized via biological routes may require additional purification steps to remove organic residues or microbial components. Ensuring the purity and uniformity of nanoparticles is essential for biomedical and pharmaceutical applications. Reliable and reproducible characterization techniques are also crucial to assess particle size, morphology, crystallinity, and surface properties (39).

5.4 Reaction Time and Yield

Compared to conventional chemical methods, biological synthesis may result in longer reaction times and lower yields. This can affect the overall efficiency and cost-effectiveness of the process, especially when high volumes are required (40).

Despite these limitations, ongoing research and technological advancements are gradually overcoming these obstacles, paving the way for cleaner and safer nanomaterial production at industrial scales(5).

-Possible Industrial Uses for Nanoparticles6

.1 Pharmaceuticals and Medicines

*Drug Delivery Systems: Drugs can be delivered directly to particular cells (such cancer cells) via nanoparticles, increasing therapy effectiveness and minimizing negative effects.

*Diagnostics and Imaging: Iron oxide and gold nanoparticles are employed as contrast agents and in medical imaging procedures such as MRI(41.(

.Agriculture.2

* Nanofertilizers: Improve plant uptake of nutrients, increasing productivity while

having a smaller e nvironmental impact.

*Nanopesticides: They target pests more precisely while using fewer chemicals and

causing less pollution.

3 .Cleanup of the Environment

* Water Purification: Pathogens, organic contaminants, and heavy metals are eliminated from water using nanoparticles such as TiO_2 and FeO_4.

* Air and Soil Remediation: When exposed to light, photocatalytic nanoparticles break down environmental contaminants(42).

4 .Energy

*Solar Cells: Nanoparticles increase photovoltaic cells' efficiency. Nanostructured materials extend the lifespan and energy storage capacity of batteries and supercapacitors.

5 .Food Industry

* Food Packaging: Antimicrobial nanoparticles increase the shelf life of food. *Food Sensors: Nanoparticles are able to identify spoiling or contamination.

6 .Textiles

*Smart Fabrics: Nanoparticles offer UV protection, water resistance, and antimicrobial

qualities.

7-Important Elements Affecting the Production of Eco-Friendly Nanoparticles

1.Reducing Agent Selection

* Eco-friendliness is ensured by using natural, non-toxic biological components (such as plant extracts and microbial enzymes) rather than harsh chemicals(43).

.2 Selection of Solvents

* Green solvents such as ethanol or water are favored over hazardous organic solvents. 3. Energy Consumption

*Techniques that don't require high temperatures, pressures, or lasers but instead function at room temperature and pressure reduce energy consumption and carbon emissions 4. Scalability of the Process

* Methods must be refined to function on an industrial scale without sacrificing the “green” advantages, not merely in tiny lab batches.

.5 Management of Physical Factors

* To preserve the quality of nanoparticles while maintaining sustainability, variables like pH, temperature, concentration of bioactive chemicals, and reaction time must be carefully regulated(44).

6 .Management of Waste Green synthesis ought to produce as little recyclable trash as possible. 7. Reproducibility and Standardization

* Creating standardized procedures guarantees uniformity, which is essential for industrial use and regulatory approval.

.8 .Source Sustainability

*The process is more sustainable when it uses abundant, renewable biomass (such as agricultural waste) rather than rare or endangered biological sources(45).

8 .Conclusion

Green synthesis represents a Effective and sustainable approach to nanomaterial production that addresses the environmental and health concerns associated with conventional methods. This review has outlined the various biological strategies employed in the clean synthesis of nanoparticles, including plant-mediated, microbial, and enzymatic approaches.

Compared to traditional physical and chemical techniques, green synthesis offers several advantages: it is cost-effective, non-toxic, energy-efficient, and allows for better control over nanoparticle characteristics. The resulting nanomaterials demonstrate high biocompatibility and functional versatility, enabling their use in a wide array of Applications in medicine, agriculture, electronics, cosmetics, and environmental science.

Although certain limitations—such as raw material variability and scalability—persist, ongoing advancements in green nanotechnology are expected to overcome these barriers. By further optimizing green synthesis processes and developing standardized protocols, researchers can contribute to more sustainable industrial practices and accelerate the integration of nanotechnology into real-world applications where sustainable nanotechnology and green-synthesised nanoparticles are already having an effect: 1. Medical Applications: Cancer Treatment and Drug Delivery Gold and silver nanoparticles that have undergone green synthesis are being employed as drug carriers for targeted cancer treatment. They assist transport medications directly to tumor cells, reducing side effects, because they are biocompatible and can be functionalized with particular molecules.

.2 Environmental Remediation: For instance, heavy metals (such as lead and arsenic) are eliminated from tainted water sources using green-synthesised iron oxide (FeO_4) nanoparticles. After treatment, they are easily separated from water due to their magnetic characteristics. 3. Nano-pesticides and nano-fertilizers in agriculture: For instance, zinc oxide (ZnO) nanoparticles

made from plant extracts are being added to fertilizers to improve nutrient delivery to crops, boosting growth while lowering pollution levels in comparison to traditional fertilizers.

4 .Food Packaging: For instance, to increase food shelf life and decrease food waste, silver nanoparticles produced by green synthesis are added to biodegradable packaging materials for their antibacterial qualities. 5. Solar Energy and Photocatalysis: For instance, solar panels and self-cleaning surfaces use biologically produced titanium dioxide (TiO_2) nanoparticles. They enhance solar energy capture and aid in the degradation of contaminants on surfaces exposed to sunlight (photocatalysis).

6 .Textiles: Antibacterial Fabrics As an illustration, greenly manufactured silver nanoparticles (AgNPs) are included into textiles (such as sportswear and hospital uniforms) to provide them resistance to odor and bacterial diseases.

7 .Cosmetics and Items for Personal Care

For instance, environmentally friendly zinc oxide and titanium dioxide nanoparticles are utilized in sunscreens because they are safer for the environment and human skin than chemically produced nanoparticles and block damaging UV rays.

Green synthesis is not only a scientific advancement but also a strategic necessity for supporting global efforts toward environmental protection and sustainable development.

9 .Conflict of Interest Statement

The authors declare that there are no known financial, personal, or professional conflicts of interest that could have influenced the content or outcomes of this publication. All authors affirm that the research was conducted independently and without any external influence.

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