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GREEN SYNTHESIS OF NANOPARTICLES: SUSTAINABLE APPROACHES AND EMERGING TRENDS

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Abstract:

Nanotechnology is a rapidly advancing discipline with a wide range of practical applications, focusing on materials that typically measure between 1and100 nanometers. Conventionally nanoparticles have been synthesized using various physical and chemical methods. In contrast, green synthesis represents a biogenic, bottom-up approach in which natural extracts act as reducing, stabilizing and capping agents.This approach is particularly significant for medical and biological applications, where nanoparticles purity is a critical factor. In green synthesis, plant extracts or microorganisms function as ecofriendly reducing and stabilizing agents, minimizing the need for hazardous chemicals. Since metal ion reduction is followed by surface modification, traditional physicochemical techniques often involve toxic stabilizers and generate harmful by-products, raising environmental and safety concerns. Natural extracts not only reduce toxicity but also help regulate the size and shape of the synthesized nanoparticles such as silver, gold, copper, iron, palladium, and lead, while also highlighting their potential applications.

Keywords: *Green-synthesis, Nanoparticles, Plant extract, Phytochemicals, nanotechnology, plants, purity*

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1.INTRODUCTION:

Nanotechnology explores a world so small that a single nanometer one billionth of a meter-fits across only about ten atoms. To imagine this scale, think of a human hair: it's nearly 150,000 nanometers thick. Large opportunities have been made possible by this small planet. This tiny world has opened big possibilities. From medicine to electronics and from agriculture to aerospace, nanotechnology lets us design and use materials that behave in entirely new ways.

Among its many branches, nanobiotechnology blends the power of biology with the precision of nanoscience. Instead of relying on harsh chemicals, green synthesis uses plants, natural extracts to create nanoparticles safely and sustainably. These biological helpers shape particles gently controlling their size and form while avoiding toxic products. Because it is cleaner, cheaper, and eco-friendly, green synthesis is becoming a promising path for producing useful nanoparticles that can heal, protect and power the technologies of the future.

1.1 Background of Nanotechnology and Emergence of Green Synthesis

Nanoparticles may feel like a gift of modern science, but their story began long before laboratories existed. Ancient artisans and healers unknowingly worked with them, guided only by the magical colors and effects these tiny particles created. silver turns yellowish -gray,20nm gold glows red like wine and platinum or palladium sinks into deep black. Long before science could explain this Artists were already using these optical tricks.

A famous historical example is the Lycurgus cup which dates back to the 4th century AD and kept in the british museum. made of dichroic glass, it shifts from green to a glowing red when light hits it thanks to hidden gold and silver nanocrystals mixed in ancient glass. Though the middle Aged, people believed ‘drinkable gold’ could cure illness and diagnose diseases. Slowly, curiosity turned into early sciences from Antoni’s Writings on colloidal gold in 1618 to Kunckel’s stained glass industry and Faraday’s famous1857 discovery that tiny gold particles create deep red solutions.

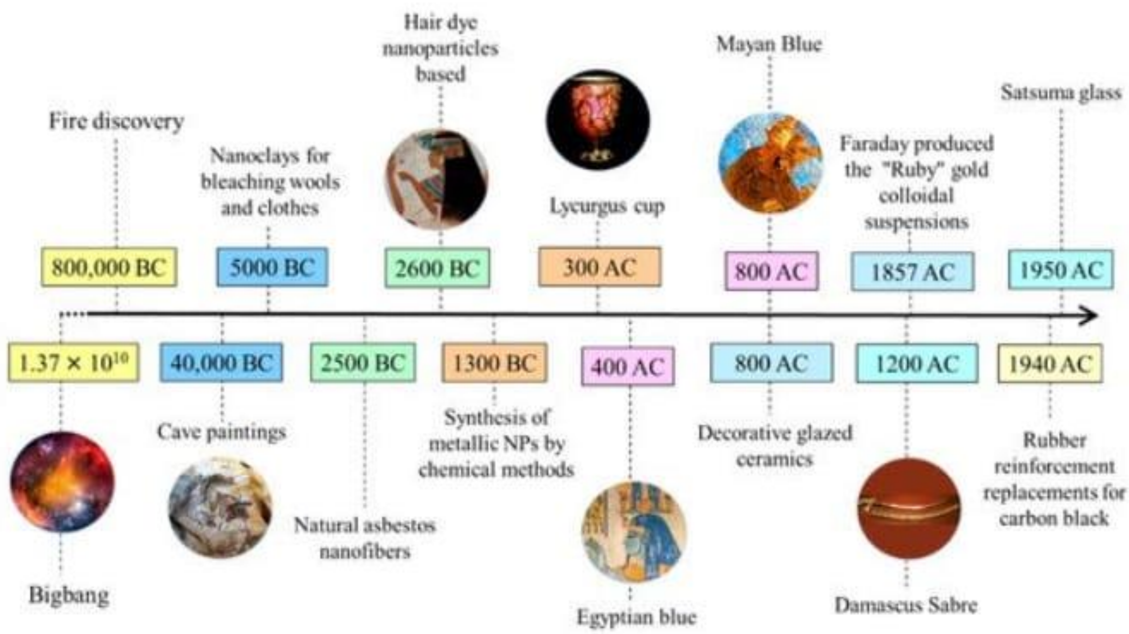

Fig.1.1: Historical Background of Nanotechnology

2. Principles of Green Synthesis:

The basic concept of green synthesis is the use of natural substances to transform metal ions into metal or metal oxide nanoparticles. Instead of harsh chemicals, this method uses plant extracts, microbes, algae, or fungi, which contain natural compounds that can reduce metal ions and help form stable nanoparticle suspensions

Additionally, these biological molecules serve as natural capping agents, coating and shielding the developing nanoparticles. This keeps them from adhering to one another, reduces toxicity, and sometimes even strengthens their antibacterial qualities, giving the finished nanoparticles a more potent overall effect.

2.1 Biological Sources used for Green Synthesis:

Traditional methods of making nanoparticles often use toxic chemicals and high energy, which can be harmful to both the environment and human health. To solve this problem, researchers began looking for eco-friendly, safe, and cost-effective ways to create nanoparticles. This led to the rise of green synthesis Green synthesis uses plants, microbes, algae and other natural materials because they have substances that can change metal ions into nano particles. These natural substances work together to reduce metal ions, stabilize the particles, and form a protective coating around the nanoparticles. These result is a faster, cleaner, and more sustainable method of producing nanoparticles without dangerous chemicals**.**

Today, biological methods for making nanoparticles are considered a highly promising approach for developing nanomaterials that are safe for medical use and environmentally friendly. Nanoparticles produced through green synthesis have been tested for many biological activities. These nanoparticles show various biological activities such as fighting microbes, reducing oxidative damage, lowering inflammation, promoting wound repair and helping to prevent cancer cell growth.

Nanotechnology has advanced so quickly that more than 1,000 consumer products now contain nanomaterials. Yet only a small number of these products fully adopt green synthesis methods. To create safer nanotechnology for long-term use, a better understanding of nature-based synthesis methods is essential.

Nanomaterials have a long history. Although modern nanotechnology seems new, humans have unknowingly used nanoparticles for thousands of years. For example, ancient artisans used metal nanoparticles to create colorful glasses and ceramics. The word “nanotechnology” however, was formally introduced later by Japanese scientist Norio Taniguchi, who described it as the processing of materials at the atomic and molecular scale.
Nanoparticles can be made using physical, chemical, or biological methods:

1. Physical Methods

Techniques like milling, laser ablation, or evaporation turn bulk material into nanoparticles. These methods often require high energy and expensive equipment.

2. Chemical Methods

Chemical reactions reduce metal ions into nanoparticles using reducing agents. These methods work well but often involve toxic chemicals that harm the environment.

3. Biological Methods

Plants, bacteria, algae, fungi, and enzymes naturally convert metal ions into nanoparticles. These techniques are affordable, easy, and eco-friendly. This is why they are becoming the preferred alternative for sustainable nanoparticle production.
Various organisms create nanoparticles that differ in size and shape.

Plants: fastest and simplest method
Bacteria: Cells are capable of producing nanoparticles within the cell and in the external environment.

Fungi: produce large quantities easily
Algae: rich in reducing compounds
Yeast: unique circumstances for particular particle types

The size and shape of nanoparticles depend on factors such as temperature, PH, concentration, reaction time, and the biological extract used. Today, researchers are especially interested in the biological activity, of green -synthesized nanoparticle. These nanoparticles have shown great potential in medicines, particularly in anti-cancer treatments. because they are less toxic and more biocompatible compared to conventionally synthesized nanoparticles. Green synthesis does not only support the idea of sustainable development but also offers a smart, modern, and environmentally balanced way of advancing Nanotechnology

TABLE 1: Nanoparticle Synthesis Using Plant Extracts

Plant source	Plant part used	Biomolecules Responsible	Type of Nanoparticles synthesized
Azadirachta indica	Leaves	Flavonoids, Terpenoids	Ag, Au,
Aloe vera	Leaf extract	Polyphenols, proteins	Ag, Au
Camellia sinensis	Leaves	Catechins, polyphenols	Ag, Au, Feo
Ocimum sanctum	Leaves	Eugenol Phenolics	Ag
Citrus Spp.	Fruit peel	Citric acid, flavonoids	Ag
Calatropis procera	Latex	Enzymes, Proteins	Ag, Au
Zingiber officinale	Rhizome	Gingerols, Zingerone	Ag

3. Methods To Create Nanoparticles:

Green synthesis aims to produce nanoparticles in a way that safe for people and the environment. This method promotes the use of natural materials and procedures that lower pollution from the start rather than producing trash or hazardous chemicals. Paul, who is regarded as the founder of green chemistry, defined it as a method of creating chemical processes that prevent pollution instead of addressing it afterwards.

Nanoparticles can be made by using two main approaches:

1.Top-Down Approach

This method starts with a bulk material and breaks it down into nanoparticles through physical process such as griding or milling. It works, but it often needs expensive equipment and may not always produce uniform particles

2. Bottom-Up Approach

Tiny building blocks such as atoms or molecules, come together to make nanoparticles. It's like assembling something from small pieces, which gives more control over shape and size. The bottom-up approach Includes

chemical synthesis: Raw materials react to form nanoparticles

Self- assembly: Molecules naturally organize themselves into nanoscale structures

Positional Assembly: Atoms or molecules are placed exactly where needed

Green synthesis fits best with the bottom- up approach because it is simpler, faster and does not require specialized machines. Plants, algae, bacteria and fungi are widely used because they contain natural compound like polyphenols, terpenes, alkaloids, proteins, and carbohydrates. These compound helps in

1. Reducing metal ions into nanoparticles
2. Controlling particle shape and size
3. Stabilizing the nanoparticles

The factors that affect nanoparticle formation are metal ion concentration, temperature, PH level, reaction duration, type and amount of plant or microbial compounds. Changing even one of these can significantly alter the nanoparticles produced

3.1 Stages of green synthesis

Green synthesis generally happens in four key phases:

1.Initial phase

A microbial culture or plant extract is made. The addition of metal salt supplies the metal ions required for creation of nanoparticles.

2. Activation Phase

Metal ions are reduced by natural substances. Nanoparticles start to create tiny "nuclei" or seeds.

3. Growth Phase

As more metal atoms cling to these small nuclei, they enlarge. Their final size and form are are influenced by temperature, pH, reaction duration and compound type.

4. Termination Phase

The final form of nanoparticles is reached. They are stabilized by natural substances, which keeps them from clumping.

3.2 Green Synthesis Method:

Plants possess exceptional capabilities for detoxifying, reducing and accumulating metals, making them a rapid, economical and environmentally sustainable option for eliminating metal-based pollutants. Owing to these natural properties, plants have become an important biological system for synthesizing metallic nanoparticles with diverse morphological characteristics. Plant-mediated nanoparticle formation can occur both intracellularly and extracellularly, depending on the interaction between plant biomolecules and metal ions.

In this approach, water containing metal ions is combined with extracts taken from various plant parts. These phytochemicals inherently present in plant extracts, including sugars, flavonoids, proteins, enzymes, phenolics, polymers, and organic acids, act as natural reducing and stabilizing agents. Natural molecules in the extracts help metal ions transform into nanoparticles that are stable.

3.3 Biological Approaches as an alternative to traditional chemical and Physical Methods:

Using green synthesis is now preferred because it is safer than traditional chemical or physical production. Conventional approaches often rely on toxic reducing and stabilizing agents, which pose risks to both the environment and biological systems. In addition, the size, shape, and surface features of nanoparticles can cause unwanted toxicity.

In contrast, biological synthesis employs naturally occurring biochemical agents present in microorganisms and plants, resulting in biocompatible and environmentally benign Nanoparticles.This technique is affordable, uses less energy and eliminates dangerous reagents. A wide variety of organisms including bacteria, actinobacteria, yeasts, molds, algae, and plants have been successfully used for nanoparticle biosynthesis. Their metabolic pathways and bioactive compounds enable efficient reduction, stabilization, and controlled growth of nanoparticles.

3.31 Bacteria-Mediated Nanoparticle Synthesis:

Bacteria are widely utilized in nanoparticle production due to their rapid growth, low cultivation cost, and easy manipulation under controlled environmental conditions. Many bacterial species possess intrinsic mechanisms for tolerating and detoxifying metals. These organisms can synthesize nanoparticles either in situ or ex situ through enzymatic pathways. In bacteria, proteins and enzymes help convert metal ions into nanoparticles that are stable.

3.32 Role of Actinobacteria: Actinobacteria-filamentous, aerobic, Gram-positive bacteria are well-known for producing bioactive secondary metabolites such as antibiotics. They are highly resistant to toxic heavy metals due to their efficient detoxification mechanisms. Toxic metal ions are neutralized through intracellular or extracellular reduction and precipitation processes. As result actinobacteria can produce nanoparticles with a wide spectrum of biological activities, including Antibacterial, Antifungal, Anticancer and Catalytic properties.

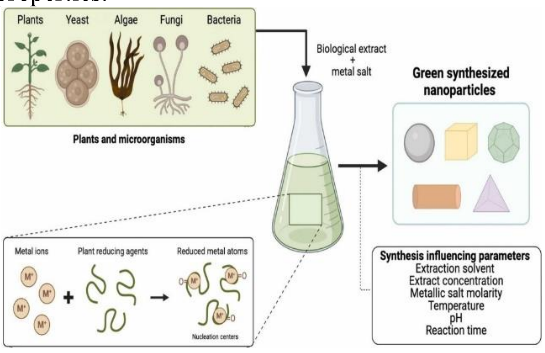

Fig.2.1: Green Synthesis Method of Nanoparticles

3.33 Yeast and Mold-Based Synthesis: Yeast and molds represent another important group of eucaryotic organisms employed in nanoparticle synthesis. They are simple to culture, grow rapidly and possess enzymatic systems that enable both intracellular and extracellular nanoparticle formation. The size and features of nanoparticles depend on the kind of metal ions, the conditions during incubation and the growth environment. However, the use of certain mold species may be restricted due to their pathogenic nature.

3.34 Algae-Mediated Green Synthesis: Algae, which can perform photosynthesis have many types of molecules like pigments, proteins, sugars, fats, nucleic acids and other compounds that can turn metal salts into nanoparticles. When algae extracts are mixed with metal solutions under controlled PH and temperature conditions, nanoparticles with antimicrobial properties can be synthesized without producing toxic- by products. The size of nanoparticles is affected by factors such as how long they are incubated, the temperature, the pH and the amount of metal ions. Algae offer additional advantage due to their abundance, ease of cultivation, and high biosynthetic efficiency.

4. Factors Affecting Nanoparticle synthesis:
The way nanoparticles form, look, and stay stable is affected by many different factors. These consist of the biomolecules present, pH, temperature, time materials and method type

4.1 Methods of Synthesis:
1.Physical methods
Techniques like arc discharge, grinding, and electron beam lithography. These usually need very high temperatures

2.Chemical methods
Includes process such as chemical reduction, electrolysis, and microemulsion. These may require moderate temperatures.

3.Biological methods
Uses plant extracts, algae, enzymes, or biomolecules. This method is non- toxic, eco-friendly works at low temperatures and is more acceptable than conventional methods.

2. pH
One important aspect of NP production is pH.it influences the rate at which the reaction occurs. Additionally, it regulates the nanoparticles stability and form. Maintaining the ideal pH enhances NP production since biological systems require it for effective operation.

3.Temperature & Pressure
Temperature has a strong effect on how nanoparticles form. Physical methods require temperatures above 350° or lower.Chemical methods also work around 350° or lower. Mild temperatures are all that biological techniques require to regulate form and stability.

4.Time
The rate at which the nanoparticles develop is influenced by time. Their nature, quality and stability while being stored. Nanoparticles may begin to group together if they are kept for an extended period of time.

5. Extract and Raw material concentration
Reaction speed, nanoparticle size, and overall stability can all be impacted by the quantity of plant extract or other natural materials utilized. Faster and smaller nanoparticles production may result from using more extract.

6. Natural Molecules and Their Functional Parts
Key Functional groups such as thiols, amines, phosphines and carboxylic acids form nanoparticles. By coating and shielding the surface of nanoparticles, these groups can serve as natural stabilizers and reducers.

4.2 Testing and Evaluation of Eco-Friendly Nanoparticles:
It is Important to analyze green-made nanoparticles to check their formation, size, shape, stability and the biomolecules involved their creation and capping. Common techniques include UV- visible spectroscopy for initial confirmation, FTIR for identifying functional groups, XRD for crystalline structure. TRM for morphology, DLS and zeta potential for stability and size distribution, and EDX for elemental composition. These techniques

together will provide a complete picture of properties.

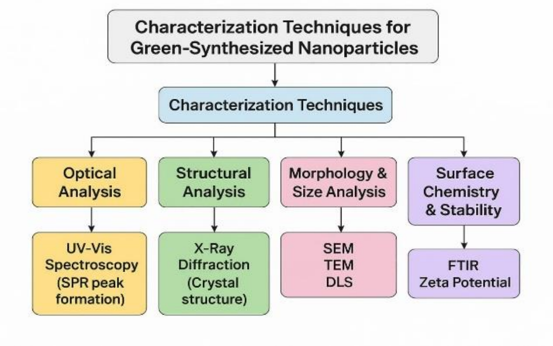

Fig.3.1: Characterization techniques for green synthesized nanoparticles

5. Uses Of Nanoparticles Made by Green Methods:

Due to their tiny size, high reactivity and special qualities, nanoparticles are used in many different fields. They are crucial to the food, pharmaceutical, paint, and agricultural, medical and environmental sectors. Below is a description of the main uses

1.Cancer treatment

Nanoparticles like gold and silver their small size makes it easier for them to pass through blood arteries. They have ability to infiltrate cancer cells, cause cell death, and halt the growth of cancer cells. They are useful and safer therapeutic instruments due to their small size, high absorption, solubility and low toxicity.

2. Site-specific drug delivery

Nanoparticles can carry drugs directly to the disease site. They provide continuous and regulated medication release. Boost medication stability and prevent the medicine from degrading within the body. Aid in the deep cellular penetration of drugs.

3. Anti-microbial Activity

Growth of dangerous viruses, bacteria and fungi. They lower the possibility of developing antibiotic resistance. They aid in the creation of novel, environmentally friendly antibacterial agents. Particularly potent, silver nanoparticles combat drug -resistant microorganisms like Bacillus subtilis and pseudomonas aeruginosa

4. Agriculture and Environment

Agriculture: Nano-fertilizers help plants absorb nutrients more efficiently. Bio-nano fertilizers like Tio_2 and Sio_2 are Preferred because they are safer and can be delivered through nanocarriers. They improve crop growth and reduce pollution from excess chemical fertilizers

Environment: Nanoparticles are used in bioremediation (removal of pollutants using metal Nps) Water purification and wastewater treatment (e.g., Mg, Tio_2) Soil purification (detection of heavy metals like Arsenic)

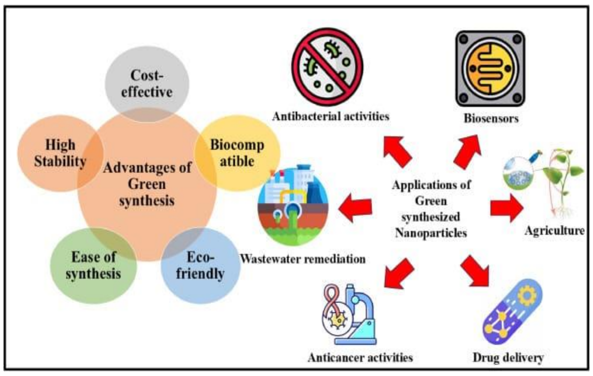

Fig.4.1: Applications of Green Synthesized Nanoparticles

6. Limitations of Green Approaches:

1. Hard to control size and shape

Because plant or microbial extracts inherently fluctuate, green approaches frequently result in nanoparticles with variable shapes and sizes.

2. Low Consistency

The content of the extracts is altered by variables such as pH, temperature, plant age, and growing circumstances. Even when the same plant is utilized, this produces different outcomes every time.

3.Unpredictable Process

It's not always clear what specific compounds are included in biological extracts. As the reaction becomes unpredictable and the formation of the nanoparticles is impossible to control.

4. Limited Control during Production

Controlling the ultimate size, stability, and homogeneity of nanoparticles becomes complex since natural extracts behave differently from manufactured compounds.

5. Not suitable for large- scale production

Typically, green nanoparticles are produces in little amounts. Commercial scale production is difficult since various qualities may be required for each batch.

6.Variable Reaction Time

The reaction could be either quick or extremely slow, depending on the kind of plant or microorganism utilized. The final nanoparticles quality is impacted by this discrepancy.

7. Poor Stability

Green-Synthesized nanoparticles may not remain stable for long. Biological materials sometimes contain impurities or reactive molecules, which affects the nanoparticle's shelf life.

7. CONCLUSION:

Green synthesis is a clean, environmentally acceptable method of producing nanoparticles. It reduces expenses, conserves resources and produces nanoparticles that are often safe and biocompatible making them helpful in biological applications such as medications. How ever this method still has some challenges. It is difficult to scale up for large production, and the results can vary because natural materials are not always consistent. There is also a need to standardize the process to the nanoparticles made each time are uniform. Overall, green synthesis is a promising and sustainable approach. With future improvements in technology and better control methods, it can become a reliable technique for producing high-quality nanoparticles on a larger scale. Nanoparticles may play a major role in the future of drug delivery. These Nanoparticles help purify water and protect crops. The impact of Nanoparticles on humans, animals, and the environment must be considered going forward.

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