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PLANT-MEDIATED GREEN SYNTHESIS OF FUNCTIONAL NANOPARTICLES: PHYSICOCHEMICAL CHARACTERIZATION AND BIOLOGICAL EVALUATION

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ABSTRACT

The research examines the mechanisms by which plants produce nanoparticles and the essential processes underlying green synthesis, which offers a safer alternative to chemical synthesis. The method allows for the creation of metallic nanostructures using plant-based compounds like terpenoids, polyphenols, and flavonoids. To fully understand bio-capped solid particles, you need to test them with UV-Vis, FTIR, XRD, and TEM/SEM equipment. The scientific studies show that this organism has a central metal structure that is protected by biological material that can kill certain types of cells while keeping harmful microorganisms from growing. The process creates a new way to make nanomedicine that is good for the environment by using plants. The method has problems because it can't make things on a large scale since it has trouble with materials of different sizes. The report says that scientists have made nanoparticles that are inspired by living things and will use them for research in agriculture and medicine in the real world.

Keywords: Nanoparticles, Polyphenols, Physicochemical, Crystalline Particles, Nanomedicine Etc

INTRODUCTION

The scientific community is currently Focused on creating sustainable production methods because nanotechnology has become vital to modern research. Scientists have traditionally used physical and chemical methods to create metal nanoparticles and metal oxide nanoparticles. The existing technologies enable users to achieve precise control over particle dimensions and particle shape specifications, but current critics raise concerns about their negative effects on environmental sustainability and economic viability. Sodium borohydride and hydrazine represent two toxic substances which chemical reduction processes use to create dangerous effects on human beings and environmental systems Anastas and Eghbali (2010). The production processes require the use of volatile organic solvents together with elevated temperature conditions and excessive energy consumption which results in the generation of dangerous waste materials that are difficult to remove. The number of researchers who investigate "Green Chemistry" principles continues to increase. We need to find new methods which prioritize biocompatibility and environmental sustainability within a short time frame.

The term "green" refers to the shift toward manufacturing goods mostly from plant materials rather than synthetic ones. The practice of plant-based synthesis has become the best environmentally friendly option because it offers affordable solutions which

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can be expanded without needing any additional capping materials Iravani (2011). The process of microbial synthesis becomes more difficult because it needs precise control to maintain both cell cultures and the necessary sterile conditions.

The tasks can be performed effectively under standard atmospheric conditions and normal indoor temperatures. The synthesis process uses plant extracts which come from different plant parts including leaves stems roots and fruits. The extract functions as a stabilizing agent which also serves as a powerful reducing agent to transform metal ions into zero-valent nanoparticles. This method uses natural nanoparticle caps instead of synthetic polymers or surfactants to protect particles from aggregation while extending their shelf life.

The complex relationship between plant chemicals found in the plant matrix initiates fundamental changes in biological systems. The natural biochemical factories in plants produce a wide range of secondary metabolites which include polyphenols and flavonoids and terpenoids and alkaloids and phenolic acids. The biomolecules contain multiple hydroxyl and carbonyl functional groups which enable effective reduction and oxidation protection. The phytochemicals during synthesis transfer electrons to metal precursors which results in the development of nanoparticles. The precise composition of these metabolites determines the final physical and chemical characteristics of nanoparticles which include their size distribution and surface chemistry Makorov et al. (2014).

The phytochemicals enable easier synthesis processes and create special functional characteristics for the synthetic nanoparticles. Bioactive plant extract compounds which "cap" the nanoparticles, demonstrate superior performance in living organisms compared to their synthetic chemical alternatives. The medical applications of the combination between an inorganic core and an organic biological shell show their most significant demonstration. The antibacterial and anti-inflammatory and antioxidant capabilities of medicinal plant nanoparticles maintain the original properties of their source plants. Plant-based nanoparticles serve as effective systems for drug delivery and wound healing and cancer detection purposes.

The current research study intends to conduct a complete evaluation of plant-mediated green synthesis methods according to their existing benefits. We investigate how different plant species create functional nanoparticles through their unique biological processes and we assess the advanced physicochemical methods that scientists use to verify particle structure. The article presents a critical examination of biological tests which demonstrate the medicinal value of "green" nanomaterials. The combination of botanical chemistry and nanotechnology provides our strongest demonstration that nature holds solutions for modern material science challenges.

Table 1

Table 1 Comparison of Synthesis Methodologies

Feature	Chemical Synthesis	Plant-Mediated (Green) Synthesis
Reducing Agents	Sodium borohydride, Hydrazine	Polyphenols, Flavonoids, Terpenoids
Environmental Impact	High (Toxic waste, high energy)	Low (Eco-friendly, sustainable)
Capping/Stabilization	Synthetic polymers (PEG, PVP)	Natural biomolecules (Proteins, Lipids)
Cost	Expensive (Pure chemicals, equipment)	Low-cost (Agricultural waste, extracts)
Scalability	Complex (Requires controlled reactors)	High (Easy to scale for mass production)
Biocompatibility	Often low (Residual toxins)	High (Naturally bioactive surfaces)

Source: Author Generated

MECHANISMS OF SYNTHESIS

Plants use two important processes to make functional nanoparticles through biochemical pathways: redox chemical reactions and supramolecular assembly systems. Plants use their proteins to change metal ions that come from salts into stable, uncharged nanoparticles. Plant extracts have a lot of reducing agents because they have a full set of metabolites that work as different reducing agents [4]. They can easily give away electrons. The efficacy of plant extracts in mitigating chemicals is contingent upon the particular configuration of phenolic compounds present in their extracts. Polyphenols are more reactive in oxidation reactions because they have many hydroxyl groups that attach to their aromatic ring structure. In plant extract solutions, the hydroxyl groups in polyphenols react with metal salts. This causes metal ions to lose electrons and protons Akhtar et al. (2013).

THE STEPS OF NUCLEATION AND GROWTH

This method puts a lot of metal atoms into one solution. The next step is "nucleation," which is when single metal atoms hit each other and stick together to make stable nuclei. The final size of nanoparticles is determined by the nucleation rate, which controls how they form. Fast nucleation events make smaller particles because they make particles that are all the same size Marslin et al. (2018). Slow nucleation phases make particles that have different size patterns. The quantity of plant metabolites is crucial, as reducing agents decrease nucleation time while producing smaller nanoparticles.

After nucleation, a process enters the growth phase. At this stage, two things are happening: nuclei are merging to make bigger particles, and metal ions from the surface are attaching to existing nuclei. Scientists use the term "Ostwald ripening" to talk about what's going on. The biomolecules in plants act as a "cap" that guides the growth of plant-based manufacturing processes in the right way. An organic material layer surrounds each nanoparticle and keeps it from growing, clumping, or losing its solution.

HOW BIOLOGICAL STABILIZATION AFFECTS THINGS

The end of their permanent condition allows nanoparticles to do their jobs. Using plant-based materials to make the protective capping layer on "green" nanoparticles is different from the usual chemical methods used to make nanoparticles. PEG and citrate are chemical stabilizers that need to be changed in certain ways before they can be used in medicine. The biological coating of plant-mediated nanoparticles is a functional part that is separate from how it is actually used Singh et al. (2018). Nanoparticles develop new biological functions by using phytochemicals that are on their surface. The functions that come from this make it easier for bacteria to get through cell walls while they specifically target cancer cell receptors. Biological caps on nanoparticles have many properties that make them stable at different pH levels and ionic strength levels. This standard is necessary for the human body and farming environments to work properly in their complex systems. The duration of a chemical reaction is influenced by environmental factors such as pH and temperature, as well as the length of the reaction itself. At alkaline pH, phenolic compounds are more likely to be reduced because protons break free from their hydroxyl groups Mittal et al. (2013). Scientists can use plants as a natural lab to make nanomaterials that work well in very specific situations. Scientists must look into the complicated methods that are part of the development process. These methods include reduction, nucleation, and capping.

Table 2

Table 2 Key Biochemical Components and Their Roles

Phytochemical Class	Primary Role in Synthesis	Example Mechanism
Polyphenols	Primary Reductant	Donation of electrons from -OH groups to metal ions.
Flavonoids	Reductant & Chelator	Formation of metal-complexes followed by reduction.
Proteins/Enzymes	Capping & Stabilization	Amine groups binding to the nanoparticle surface.
Terpenoids	Reducing Agent	Transformation of carbonyl groups during the redox cycle.
Sugars/Glucosides	Stabilizer	Steric hindrance to prevent particle aggregation.

Source: Author Generated

PHYSICOCHEMICAL CHARACTERIZATION

The successful production of plant-mediated nanoparticles represents merely the initial phase in an extensive scientific endeavor. Before they can be used, it must be confirmed that they are formed, that their structure is sound, and that their physical properties are known. Physicochemical definition is the connection between creating something from scratch and using it in a way that is helpful Thakur et al. (2019). This section goes into a lot of detail about the tests that were done to make sure that the biological reduction of metal ions really did make nanoparticles that were stable and useful.

UV SPECTROSCOPY AND SURFACE PLASMON RESONANCE

Using ultraviolet-visible (UV-Vis) spectroscopy is the best and easiest way to show that nanoparticles have been made. This method is based on a physical effect called Surface Plasmon Resonance (SPR). This happens when the conduction electrons on the surface of a metal nanoparticle vibrate in sync with the electromagnetic radiation of light. The visible spectrum shows a strong peak because metallic nanoparticles such as gold (Au) and silver (Ag) exhibit resonance in this range Link and El-Sayed (2000). The SPR peak for silver nanoparticles exists between 400 and 450 nanometers while gold nanoparticles show an absorption band that extends from 520 to 560 nanometers. The peak's position and height and width provide essential information about the synthesis process. A narrow, symmetrical peak means that the particles are evenly spread out and round. A broad peak or multiple peaks means that the particles are not evenly spread out and are making shapes that are not round, like nanorods or triangles.

FTIR ANALYSIS OF THE INTERFACE BETWEEN BIO AND ORGANIC

UV-Vis shows that there is a metallic core. The complete understanding of plant extract organic "shell" or capping layer requirements requires Fourier Transform Infrared (FTIR) spectroscopy. the FTIR method enables researchers to identify the various functional groups present on nanoparticle surfaces through analysis of bond vibrations. The researchers use FTIR spectra from both raw plant extract and synthesized nanoparticles to identify which phytochemicals participated in the stabilization and reduction processes. Peaks which correspond to hydroxyl (-OH) and carboxylic acid (C=O) and amine (N-H) groups usually exhibit movement or complete disappearance. The phenolic -OH stretch at 3300 cm^{-1} decreased in strength because the metal ions were reduced, which caused the oxidation of these groups Modun et al. (2020).

The method provides information about material crystallinity and phase composition. Scientists can use this method to demonstrate that nanoparticles have a crystalline structure while they determine the current phase of the nanoparticles. Green-synthesized silver nanoparticles show X-ray diffraction (XRD) patterns that display distinct peaks at 2θ positions matching the (111), (200), (220), and (311) crystallographic planes of face-centered cubic (fcc) lattice structure. You can tell how crystalline something is by how sharp these peaks are; clear, strong peaks mean that the crystal structure is very well organized. You can also use the Scherrer equation, which links the peak widening to the size of the internal crystal domains, to find the average size of a crystallite. This mathematical proof is a very important way to compare the sizes seen under a microscope.

Using SEM and TEM electron microscopy to find out the shape is the clearest way to show that nanoparticles are made. The tools used for scanning electron microscopy (SEM) make high-quality pictures that show details about the surface and the shape of the material. Scientists always use Transmission Electron Microscopy (TEM) process to explain nanotechnology objects in the best way possible in this way Rabiee et al. (2020). The TEM pictures show an organic "halo" that spreads out from the metal core in the middle. The synthesis step gives us visual proof that the capping process has happened. Scientists use TEM to learn about the boundary points that make up the lattice structures of nanoparticles. This proof shows that their crystal structures are similar, which backs up what was found through XRD testing.

To study dry nanoparticles, you need to measure their Zeta Potential and Dynamic Light Scattering (LDS). We can learn how they behave in liquids by looking at them. Dynamic Light Scattering (DLS) is the technique employed to ascertain the mobility of nanoparticles in liquids. The measurement point shows where the metal structure ends and the water next to it begins. The water layer has capping agents that come from plants. The DLS measurements give higher value results because they show more particles than the TEM methods do. We can find out the size and surface electrical properties of nanoparticles using the Zeta Potential method. The absolute Zeta Potential measurement is more than +30 mV, which means that particles will feel strong electrical forces that pull them together. The colloidal suspension stays stable. When plants are used in synthesis, the negative charge that carboxylate or phosphate groups in the plant extract give off helps keep the nanoparticles stable and stops them from settling down.

Table 3

Table 3 Summary of Analytical Techniques and Their Functions

Technique	Abbreviation	Information Provided
UV-Visible Spectroscopy	UV-Vis	Confirmation of SPR peak; preliminary size/shape estimate.
FTIR Spectroscopy	FTIR	Identification of phytochemical functional groups (capping agents).
X-ray Diffraction	XRD	Crystallinity, phase identification, and average crystallite size.
Transmission Electron Microscopy	TEM	Exact morphology, size distribution, and lattice structure.
Scanning Electron Microscopy	SEM	Surface topography and particle clustering/aggregation.
Dynamic Light Scattering	DLS	Hydrodynamic diameter and particle size distribution in solution.
Zeta Potential	ZP	Surface charge and colloidal stability assessment.

Source: Author Generate

BIOLOGICAL EVALUATION

The most valuable thing about plant-mediated nanoparticles is that they can do so many biological functions, not just how pretty they look. The "Green" method of synthesis creates a unique contact point between an inorganic metallic core and a bioactive organic corona made from plant secondary metabolites Bhattacharya and Gupta (2005). Nanoparticles that have both properties are often better at interacting with living things and being friendly than nanoparticles that were made chemically. In this section, we will go into more detail about the three main areas of biology where these nanoparticles really shine: they can kill microbes, they can act as antioxidants, and they can kill cancer cells.

WHAT ANTIBIOTICS DO AND HOW THEY DO IT

One of the most studied uses of nanoparticles that plants make is their ability to kill germs. This is especially true for copper oxide (CuONPs) and silver (AgNPs). Nanoparticles fight bacteria in many different ways, so it is much harder for bacteria to become resistant to them. Some medicines only change a few metabolic processes, but this one changes a lot of them.

Electric forces hold microparticles to the walls of bacteria cells. This is how they begin to kill the germs. Nanoparticles hurt cells when they stick to their surfaces. This makes the membrane more permeable, which lets important chemicals and proteins leak out of the cell. Also, when these nanoparticles get inside a cell, they let out metal ions (Ag^+ or Cu^{2+}) that stick to the thiol groups of important transport and enzyme proteins, which stops them from doing their jobs Dakal et al. (2016). Nanoparticles can make Reactive Oxygen Species (ROS) because they can make cells react. Free radicals are what cause oxidative stress during this process. This damage to DNA stops bacteria from making copies of themselves. It works better to use plant-based materials for caps than other types of materials. The nanoparticles have a "double-punch" effect because they are naturally covered with essential oil parts like carvacrol or thymol. This makes the bacteria's lipid bilayer even less stable.

POSSIBILITY OF ANTIOXIDANTS AND RADICAL SCAVENGING

The generation of reactive oxygen species through ROS production serves as a bacterial elimination method in which researchers utilize nanoparticles that possess both antioxidant properties and biological coating effects which benefit human health. The manufacturing process of plant-mediated nanoparticles results in phenolic chemicals and flavonoids which adhere to their surface to create all their antioxidant capabilities. The compounds maintain their ability to provide hydrogen atoms and electrons to free radicals despite their binding to the metal core Bondarenko et al. (2013).

The ABTS assay and DPPH (2 2-diphenyl-1-picrylhydrazyl) scavenging assay serve as standard methods for evaluating this particular effect. The capacity of nanoparticles to eliminate free radicals depends on their quantity present in the environment. The treatment of diabetes and neurodegenerative disorders which develop chronic inflammation and oxidative damage requires this process to achieve successful outcomes. The metal core functions as a catalyst which enhances the antioxidant properties of phytochemicals that bond with it more than the extraction from the plant itself.

TOXICITY TO CELLS AND ACTIVITY AGAINST CANCER

Nanomedicine studies plant-based nanomaterials to see if they could be used to treat cancer. The scientists want to make "smart" nanoparticles that only kill cancer cells and not healthy cells. Green nanoparticles that have AuNPs and ZnONPs properties can kill certain types of cells. This happens because cancer cells' metabolism changes. The substances are acidic and are always oxidizing.

The endocytosis process that happens with these nanoparticles kills cancer cells. The process starts with the activation of proteins, which kills cells and breaks down nuclear DNA. Studies show that nanoparticles from turmeric and green tea are good for your health. Curcumin and EGCG, which kill cancer cells, are in the capping layers of the particles. These substances tell the nanoparticles to go to certain cancer cell receptors Kedziora et al. (2018). The nanoparticles have a lot of surface area, which lets bioactive compounds get to tumors. When this happens, the scientists look at MCF-7 breast cancer cell lines and HeLa cervical cancer cell lines Jacob et al. (2012). The chance of inflammation happening goes down. In hemolysis testing, green nanoparticles usually don't go over the 5% limit for medical devices. The test results show that they keep blood flowing normally.

Table 4

Table 4 Summary of Biological Activities

Biological Assay	Targeted Effect	Key Observation
Antimicrobial (MIC/MBC)	Bacterial Growth Inhibition	Destruction of cell wall and ROS generation.
Antioxidant (DPPH/ABTS)	Free Radical Neutralization	Phytochemical-mediated electron donation.
Cytotoxicity (MTT/XTT)	Cancer Cell Death	Selective apoptosis and DNA fragmentation.
Hemolytic Assay	Blood Compatibility	Low RBC rupture indicating high safety profile.
Anti-Inflammatory	Protein Denaturation Inhibition	Stabilization of lysosomal membranes.

Source: Author Generated

CHALLENGES AND FUTURE PERSPECTIVES

Researchers are doing a lot of work on plant-mediated synthesis. The biological results show that the lab work is very good, which makes it hard to move from "bench to bedside" and from lab equipment to industrial production. The new green ways to make nanoparticles are better for the environment than old chemical methods. There are still big problems that need to be worked out before hospitals and everyday life can use these useful nanoparticles.

HOW TO HANDLE POLYDISPERSITY AND REPRODUCIBILITY

The first issue with green nanotechnology research is that it needs to be more standardized. When scientists use pure materials in controlled settings to do chemical synthesis tests, they make nanoparticles that the are all the same size and shape. The extraction process makes complicated plant extracts that give results that vary because of how plants are made Gnanadhas et al. (2013). The age of the plant, where it was brought from, the weather, and the time of year when the sample was taken all affect how many secondary metabolites the plant system makes. There is no doubt that outcomes will lead to outcomes that vary. Aloe vera harvested from a certain place makes the nanoparticles with dimensions up to 20 nanometers wide. An extract of aloe about a different place utilizes the particles that are 10 to 100 nanometers across and can be either round or triangular. This strange behavior makes it harder for regulators to approve drugs for use. This is because the size of nanoparticles affects how they work and how harmful they are. Researchers in this manner must standardize plant products to maintain their presence to ensure consistent results in synthesis nature Nel et al. (2009). To accomplish this exact goal more effectively, researchers here should employ refined polyphenol fractions instead of unprocessed samples.

BRINGING TOGETHER DIFFERENT INDUSTRIES AND THE ABILITY TO GROW

In the lab, you only need a few milliliters to make nanoparticle solution, but in industry, you need hundreds of liters. To work in a way that is good for the environment, the process uses too much water and fuel. To get nanoparticles out of plant material, the extraction process needs industrial-scale filtration and centrifuge equipment. When compared to artificial caps that contain PEG, the biological cap does not stay stable over time. When nanoparticles get close to breaking down completely, the organic acids on their surfaces will start to lose their stability. The particles will stick together, which will make them lose their useful properties. The business needs to come up with ways to keep their products' "green" qualities while also making them last longer on store shelves.

RULES AND SAFETY FRAMEWORKS

Because of their overall unique biological properties, green nanoparticles here are very hard for the medical field to control for nowdays. The FDA & EMA always want to know everything about the chemicals which is or not to be a drug. The "corona" of plant-based nanoparticles is made up of lipids, phenolic compounds, & several proteins. We still don't know most of these Pal et al. (2011).

The biological shell works by connecting with plasma proteins in the body to make the "protein corona" system. The nanomaterial may pose safety concerns if the plant-based coating modifies immune system functions and if the antioxidant components produce unforeseen effects. Scientists need to do more live animal research to find out how complex animal models move particles around their bodies, how quickly they get rid of them, and which particles cause long-term damage.

IN THE FUTURE: TOWARD "DESIGNER" GREEN NANOPARTICLES

Scientists don't use trial and error to test out different plant products anymore. They have come up with a way to find the best plant chemicals that work with certain metal ions by combining genetic information with computer simulations. Many people are interested in "Nano-Agrotechnology," which uses tiny green particles to kill weeds and improve the nutrients in the soil. In this case, the nanoparticles will help the nutrients leave the plant system slowly. The method will help save water by making it so that gardeners don't need to water their plants as much.

FINAL THOUGHTS

Researchers developed a synthetic method which uses plant properties to create a process that eliminates the environmental and economic limitations of traditional chemical and physical methods. The review shows that the process operates as a cleaner alternative because it functions as an advanced biochemical system which generates nanoparticles with unique physical and chemical properties. Phytochemicals build the metallic core while they help the biological shell perform its functions. The process generates nanoparticles which demonstrate outstanding strength together with their ability to coexist with living organisms.

The scientists used UV-Vis and FTIR and XRD and electron microscopy to investigate the physicochemical properties of these "green" particles. The results showed that the particles maintained their original shapes and displayed high crystallinity which matched the results of more stringent industrial processes. The issue of drug tolerance continues to escalate while people seek more precise solutions for their cancer treatment needs. The nanoparticles provide treatment capabilities because they can address multiple diseases simultaneously.

Medical application and industrial implementation of laboratory testing success needs to solve three main challenges which include reproducibility issues and standardization efforts and regulatory system complexities. Research needs to progress through its entire process which begins with observation and ends with controlled experimental design. Scientists can enhance the efficiency of green processes while simplifying their implementation through their industrial operations by studying plant energy utilization and improved data analysis methods. Plant-mediated synthesis demonstrates the complete potential of "nature-inspired" engineering design through its successful application. Scientific progress and environmental protection can coexist as complementary forces because they support each other's development.

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