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EXPLORING THE GREEN SYNTHESIS OF NANOPARTICLES AND THEIR MULTIFACETED IMPACT ON BIOMEDICAL APPLICATIONS AND ENVIRONMENTAL REMEDIATION: A REVIEW PAPER

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Abstract

Nanoparticles have attracted significant interest in recent years due to their distinctive characteristics and wide-ranging uses in different domains. Nanoparticle production using environmentally friendly technologies has become a sustainable and eco-friendly alternative to traditional chemical processes. This review comprehensively explores the various green synthesis techniques employed for the production of nanoparticles, including those utilizing plant extracts, microorganisms, enzymes, and agricultural waste. Additionally, the multifaceted impact of green-synthesized nanoparticles on biomedical and environmental applications is elucidated. In biomedicine, these eco-friendly nanoparticles exhibit promising potential in drug delivery, diagnostics, and targeted delivery capabilities. Furthermore, their applications in environmental remediation, including pollutant degradation, heavy metal ion removal, and wastewater treatment, highlight their significance in addressing contemporary environmental challenges. The review also discusses the key properties and mechanisms underlying the enhanced performance of green-synthesized nanoparticles in biomedical and environmental applications, emphasizing their sustainable nature and reduced environmental footprint. Moreover, challenges and future perspectives in the synthesis and utilization of green nanoparticles are critically examined, aiming to pave the way for the development of innovative and sustainable nanotechnologies.

Keywords: *Green synthesis, nanoparticles, biomedical applications, environmental impact, sustainable nanotechnologies.*

1. INTRODUCTION

Green nanotechnology is a relatively new field of study that tries to address issues related to conventional nanomaterial production and its impact on the environment and human health. It does this by combining nanotechnology with sustainable practices. As the detrimental impacts of traditional manufacturing processes on the environment become more widely acknowledged, there is a huge demand for sustainable and environmentally acceptable ways for creating and employing nanoparticles. Green nanotechnology combines a number of techniques to minimize the use of hazardous chemicals, boost the use of renewable resources, and consume less energy. Green nanotechnology holds great promise for revolutionizing numerous other industries and providing long-term solutions to pressing global issues. [1]. This dynamic and constantly evolving discipline has a significant impact on biotechnology and biomedical science in particular [2-4]. Multifunctional nanomaterials have been developed by the field of nanotechnology, which has led to their application in several industries and disciplines of study, such as energy storage, optics, medicine, solar cells, food, cosmetics, paints, and so on. [5]. These remarkable applications of nanomaterials [6–10] span numerous disciplines, including biomedical science, energy technology, electronics, electric chemistry, food processing, medical treatment, mechanical work, membrane modification, transparent products, drugs, sensors, the aerospace industry, textiles, and water purification. In development are nanospheres, nanorods, nanoneedles, nanocubes, nanoplates, and an innumerable number of other nanoparticle morphologies. The investigation of substances and structures measuring from one meter in length to one hundred nanometers is referred to as nanotechnology, as defined by the National Science Foundation of the United States. Research in this field focuses on manipulating the chemical and physical properties of substances at the nanoscale before integrating them into larger frameworks [11,12]. Nanoparticles' (NPs) exceptional surface area and distinctive chemical and physical properties have elevated their profile considerably in recent times [13, 14]. In excess of USD 27 billion has been allocated to this sector by the National Nanotechnology Initiative of the United States government over the past decade. In addition, the European Commission has invested approximately 1.1 billion euros in numerous nanotechnology companies through the Horizon 2020 program [15].

Green nanotechnology holds great promise to transform the medical industry through the creation of biocompatible nanoparticles that exhibit reduced side effects and increased effectiveness. Drug transport, diagnostics, and therapeutic applications could all benefit from the application of these nanoparticles [16]. Polluted places can be restored, water can be cleaned, and pollutants can be identified with nanoparticles produced with eco-friendly ways [17]. Other agricultural applications of green nanotechnology include fertilizer delivery systems, pest control, and crop enhancement. Nanoparticles made with environmentally friendly methods can help make sustainable electronic devices that function better and generate less trash.

The field of nanotechnology has the potential to significantly impact medical, biological, and related disciplines by offering unparalleled opportunities to investigate and regulate numerous processes at the nanoscale [18]. Nanocarriers offer unique advantages in the areas of diagnostics, targeted medication delivery, antibacterial activity, and anticancer action. A wide range of nanomaterials have drawn interest in the field of biomedicine, including carbon nanotubes, compounds based on nanogel, liposomes, nanocapsules, nanofluids, nanowires, and nanoparticles (NPs). Research on their potential medical applications has concentrated on topics such drug transport, antimicrobial applications, cancer diagnosis and therapy, biocompatibility and appropriateness, and medication administration [19–21].

Green nanoparticles are used in environmental remediation for a variety of purposes, including air pollution control, antibacterial agents, and water and soil cleaning [22–25]. The environment is now cleaner and greener as a result of their skill in cleaning up after pollution. The application of green nanoparticles in photovoltaics and energy storage has also shown promising outcomes. By improving the functionality and efficiency of solar cells and storage devices, these technologies hope to contribute to the development of sustainable energy solutions. They offer opportunities for the food and cosmetics industries to develop safer products with superior formulas [26, 27]. They provide precise compound detection and monitoring since they are sensors. Additionally, they present chances for new applications and enhanced usefulness in the textile and electronics sectors [28]. As shown in Fig. 1, green nanoparticles have the potential to transform a number of industries, such as nanosorbents, nanoelectronics, and catalysis.

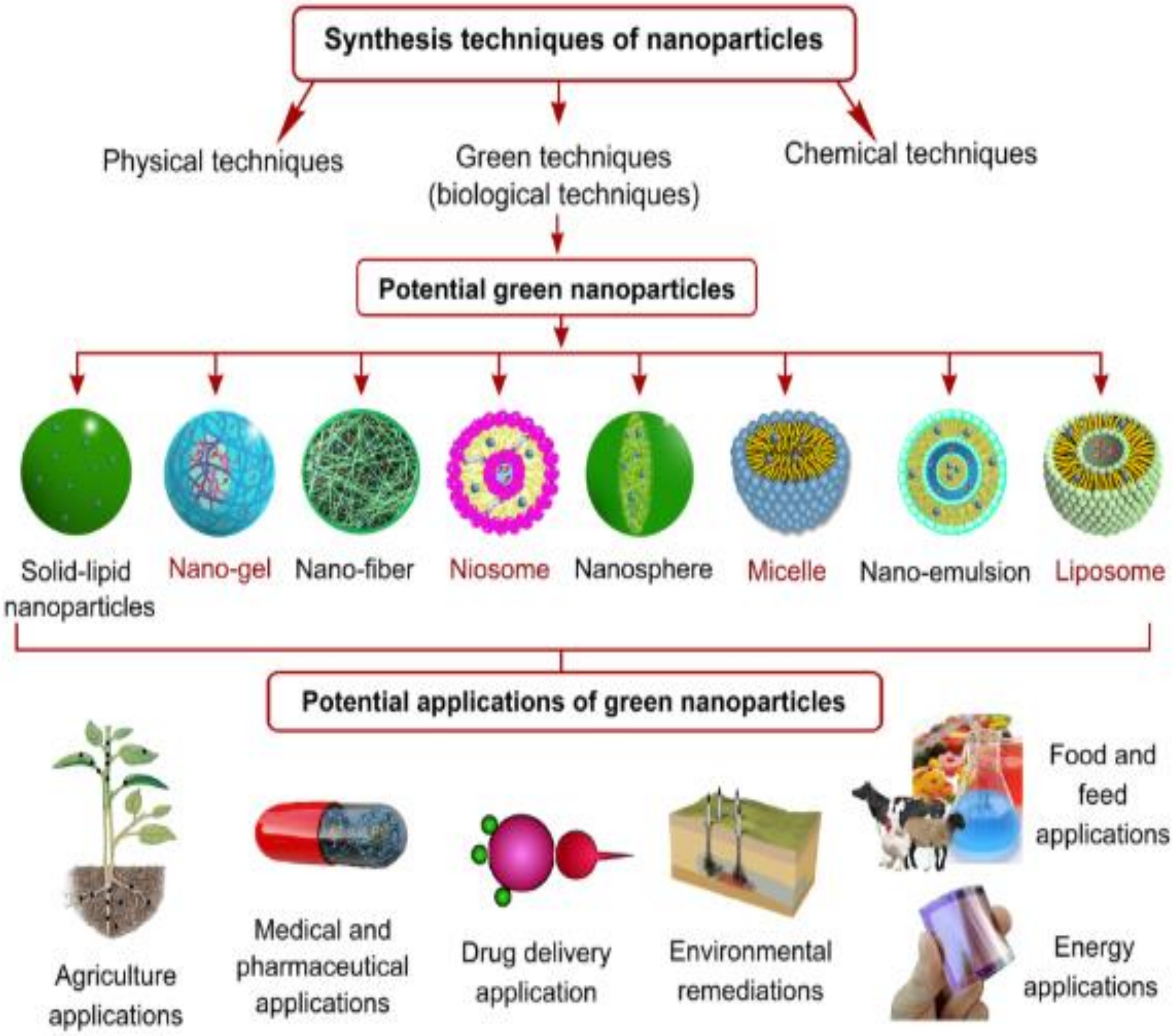

Fig. 1: Synthesis techniques of nanoparticles

Therefore, this review is distinctive in that it thoroughly examines the diverse applications of green synthesis methods. The potential of green-synthesized nanoparticles to facilitate substantial industry revolutions and make a positive contribution to sustainability. Additionally, it investigates the utilization of these nanoparticles in the fields of agriculture, medicine, environmental remediation, and sustainability. Green synthesis methods are appealing to businesses and researchers in search of sustainable alternatives owing to their efficiency, environmental tolerance, and biocompatibility. To promote the pragmatic implementation of nanoparticles, it is critical to address several obstacles, including reproducibility, stability, and size and shape regulation.

2. Routes of Green Synthesis of NPs

Nanoparticles can be produced in many different ways, but two primary types exist: chemical and biological. The former group uses precipitation, sol-gel, micro-emulsion, and steam condensation as methods. Algae, plants, fungi, yeast, bacteria, and sugars (such as glucose, starch, and cellulose) are just a few of the sources that are utilized in biological processes, as seen in Figure 2 [29, 30].

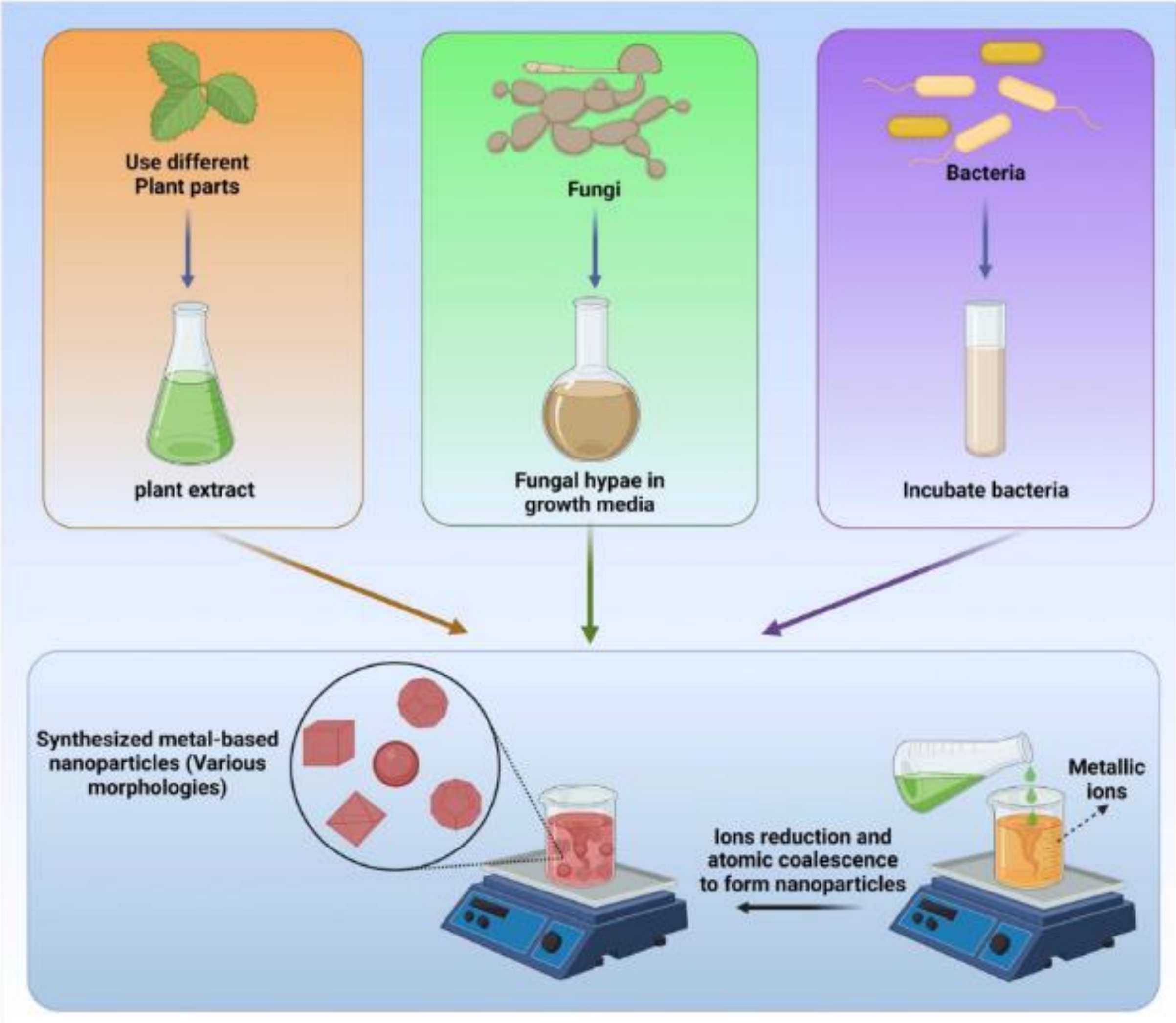

Fig. 2: Biological approaches to obtain green synthesized nanoparticles

2.1. Synthesis by Microbes

Microbes such as yeast, fungi, and bacteria have the ability to decrease metal ions, which enables them to create nanoparticles. The specific mechanisms can be influenced by the type of microorganisms present and the kind of nanoparticles being produced.

- **Extracellular Enzymes:** Microbes produce extracellular enzymes called reductases, which can help reduce metal ions in the growth media. These enzymes act as biological reductants by giving metal ions an electron, which reduces the ions and finally forms nanoparticles [31].
- **Metabolic Pathways:** Metabolic processes found in microbes can play a role in nanoparticle formation. As an example, certain microbes can produce nanoparticles as a byproduct of reducing metal ions through their electron transport chains, which they obtain from respiration or photosynthetic processes. This metabolic pathway for nanoparticle manufacturing is clean and safe for the environment.
- **Biomolecule-Metal Interactions:** Biomolecules such as proteins, peptides, polysaccharides, and secondary metabolites released into the environment by bacteria have the ability to decrease and stabilize metal ions. These biomolecules function as reducing, capping, and stabilizing agents, influencing the size, shape, and surface characteristics of nanoparticles.
- **Intracellular Synthesis:** Metal ion uptake into cells enables intracellular reduction and nanoparticle production in certain bacteria. Collaborating with intracellular biomolecules like enzymes or specialized binding proteins, metal ions enable the reduction and assembly of nanoparticles within microbial cells.

The specific pathways and processes that microorganisms use to synthesis nanoparticles can be influenced by the growth environment and metal precursors used. Researchers have been working to gain a better understanding of the underlying mechanisms in order to customize the microbial synthesis process to specific needs. The creation of nanoparticles that rely on internal ion transport is significantly influenced by the microbial cell wall. "Ion entrapment" is the result of positively charged metal ions coming into contact with negatively charged cell walls through electrostatic fields. Metal nanoparticles are created when enzymes found in cell walls liberate ions that have been trapped. Control over the size, shape, agglomeration, surface energy, grain formation, dispersion, capping agents, and electrostatic and steric hindrance of nanoparticles can be achieved by adding appropriate functional groups to their surfaces. Coating agents offer a number of benefits, including uniform manufacturing, controlled toxicity levels, and storage stability (for biological extracts) [33]. When eliminating non-cellular nanoparticles from bacterial samples, centripetal force is a helpful instrument. After the supernatant containing the nanoparticles has been collected, more incubation is accomplished by adding a metal salt solution. The culture media's color changing is an obvious indicator that nanoparticles are forming [34].

2.2. Synthesis by Plants

2.2.1. Mechanism

Green synthesis nanoparticle production requires plant extracts that include bioactive compounds that lower the concentration of metal ions in the precursor solution. The specific procedures could vary depending on the kind of nanoparticle and plant extract being studied. The primary procedures in the environmentally acceptable synthesis of nanoparticles from plant extract.

- **Reducing Agents:** Plant extracts contain a wide variety of bioactive substances, all of which have lowering effects. Polyphenols, flavonoids, and terpenoids are only a few of them. These substances have the dual properties of stabilizing and reducing when utilized in the synthesis of nanoparticles. Contributing electrons to the metal ions in the precursor solution is one method of facilitating the reduction and formation of nanoparticles [35].
- **Capping and Stabilization:** Plant extracts contain a variety of biomolecules, including proteins, polysaccharides, and organic acids, which can cap and stabilize nanoparticles. These biomolecules attach to the surface of the nanoparticle, stabilizing it and preventing it from aggregating. The size, shape, and surface properties of the generated nanoparticles are also influenced by capping agents.
- **pH and Temperature:** The synthesis of environmentally friendly nanoparticles can be significantly impacted by the pH and temperature of the reaction media. An optimal pH environment that promotes metal ion reduction is necessary to control the nucleation and growth of nanoparticles. Temperature-dependent reaction kinetics have an impact on the size and structure of synthesized nanoparticles [36].
- **Nucleation and Growth:** The bioactive compounds reduce metal ions, which leads to the formation of nucleation sites that are capable of producing nanoparticles. In order to increase the size of nanoparticles, the growth process involves reducing and depositing metal ions onto the preexisting nucleus. A few factors that affect the nucleation and growth rate are the stirring parameters, reaction duration, and precursor ion concentration.

Plant extracts are used in a typical, multi-phase process for the manufacture of metal nanoparticles. Boiling the plant extract and then sifting it thoroughly yields a clear aqua extract, which is ideal for forming nanoparticles. Subsequently, a metal salt solution is added to the aqua extract to continue the incubation process. For example, the production of synthetic nanoparticles would be indicated if the fluid turned dark rather than yellow. Stems, roots, bark, leaves, flowers, fruits, and seeds are just a few of the plant parts that have been used to produce NPs in an environmentally friendly manner. Utilizing these plant extracts can result in reduced and stabilized conditions [37, 38]. Natural materials like polysaccharides are excellent NP building blocks [39]. Note that the specific mechanisms of green synthesis-generated nanoparticles can be influenced by the metal precursor content, the reaction conditions, and the plant extract content.

3. Impact of Experimental Parameters on the Formation of the NPs

The characteristics and qualities of nanoparticles are quite susceptible to many elements taken into account during their manufacturing process. These impacting factors need to be adjusted and controlled in order to produce nanoparticles with the proper size, shape, composition, stability, and other characteristics. Among other important factors, temperature, pH, metal ion concentrations, and reaction time all affect the creation of nanoparticles.

3.1 Temperature

Temperature plays a significant role in the synthesis of nanoparticles because of its impact on reaction rate, nucleation, and growth. NPs have been produced in a range of shapes and sizes, including triangles, octahedral platelets, spherical, and rod-like, at varying temperatures [40]. For instance, at 20 °C, we made triangular-shaped Au NPs using Piper betel leaf extract, and at 30-40 °C, we made octahedral-shaped NPs with a diameter of 5–500 nm. At temperatures between 50 and 60 °C, more homogeneous nanoparticles (NPs) were generated in a parallel orientation to the nanotriangles. Morganella psychrotolerant can be used to create round AgNPs with an average diameter of 2–5 nm at 20 °C, which is the ideal growth temperature. On the other hand, at 25 °C, several shaped nanoplates, such as spherical NPs, hexagons, and triangles, were created. Particles exposed to higher temperatures may clump together or even expand uncontrollably, even though they can speed up reactions. Therefore, the key to producing nanoparticles with the desired properties is finding the ideal temperature.

3.2 pH

The pH, or hydrogen ion concentration, is another crucial element in the formation of nanoparticles. pH regulates nucleation centre formation in a manner akin to that of temperature. Since a rise in pH increases the number of nucleation centres, enhanced formation of metallic NPs is correlated with an increase in pH. The NPs' form is also influenced by pH in addition to size. Two instances of this include the generation of intracellular NPs by fungi in an acidic environment (pH 5.5–6.6) and the creation of an Au-NP nano-conjugate by Rhizopus oryzae mycelia in an acidic environment (pH 3) [41]. NPs ranging in size from 25 to 85 nm were seen to form in minute numbers at a low pH (pH 2). Since fewer nucleation sites develop at lower pHs, theoretically Au-NPs are less likely to aggregate into large-sized NPs. The stability, aggregation propensity, and surface charge of the nanoparticles all vary in response to variations in the hydrogen ion concentration. Greater size particles are produced at lower pH levels than at higher acidic pH levels. The ideal pH must be reached for nanoparticles to have the desired properties.

3.3 Concentrations of Metal Ions

Metal ion concentrations, which are often seen in metal salt solutions, are also crucial for the creation of nanoparticles. Because of their influence on nucleation and growth, particles can have different sizes, distributions, and compositions. On the one hand, nucleation and particle formation can proceed more quickly when exposed to higher concentrations of metal ions. However, they can also lead to an increase in particle clustering or even unintentional crystallization. Higher concentrations of AgNO3 produced a nanoparticle that quickly aggregated when AgNPs were synthesized from C. microphylla extract, as an example of the point. Changes in the volume percentage of metal ions can have an impact on the stability and optical properties of the nanoparticles. Determining the optimal concentration of metal ions is crucial when modifying the properties of nanoparticles.

3.4 Reaction Time

Reaction time is one of the many variables that influence the structure and behavior of nanoparticles. Their activities have an impact on the stability and maturation of nanoparticles. Longer response times can lead to accelerated particle production, aggregation of particles, or changes in crystal structure. The idea was verifiable since when the solution was made from ferric nitrate using green tea extract, a longer reaction time led to more FeNPs. Excessive incubation time may lead to reduced nanoparticle potential due to aggregation or shrinking. The amount of bio-compounds in the extract significantly affects the metallic nanoparticles' size and distribution. The strong reductant in the extract promotes a quick reaction rate and the creation of more controllable nanoparticles. Achieving the required outcomes requires determining the ideal reaction time, which may be used to influence the stability and other properties of nanoparticles.

The synthesis of nanoparticles can be affected by an extra set of variables, such as the kind and quantity of the solvent, the conditions under which it is mixed or stirred, the presence of surfactants or additives, and the type and quantity of stabilizing and reducing agents. These variables may have an impact on the stability, growth, nucleation, and surface characteristics of the nanoparticles. To produce nanoparticles with the necessary stability, composition, size, shape, and other attributes, controlling and optimizing the influencing parameters involved in nanoparticle synthesis is crucial. Understanding how these factors affect the synthesis process can help us make tailored nanoparticles that have applications in healthcare, electronics, energy, and environmental remediation, among other sectors.

4. Biomedical Applications

4.1 Anticancer Activity of Nanoparticles

Cancer is one of the main causes of death worldwide, with millions of new cases reported each year. Despite significant advancements in our understanding of the genetic and environmental factors that contribute to cancer, the conversion of scientific discoveries into effective cancer diagnostics and therapies has proven to be a difficult challenge. Occasionally, conventional cancer treatments are ineffective or may cause adverse consequences that damage healthy tissues. By allowing targeted drug delivery and overcoming biological barriers in a way that is minimally damaging to neighboring cells and inconspicuous to the immune system, nanotechnology holds the potential to completely transform cancer diagnosis and treatment [42, 43]. HepG2 human liver cancer cell lines and the antitumor properties of environmentally generated silver nanoparticles made from Carica papaya. Tested against the human breast cancer cell line MCF-7, the cytotoxicity of the green silver nanoparticles was determined to be roughly 10 μg/mL after a 24-hour incubation period. It grew threefold in the next day. Studies on the anti-proliferation effects of silver revealed that it also shrunk the MCF-7 cell line. Acridine orange and ethidium bromide staining was used to confirm, after 24-72 hours, the ability of silver nanoparticles to induce cell death in HepG2, MCF-7, and A549 human lung cancer cell lines [44]. It was also discovered that Mentha longifolia-derived gold nanoparticles were effective in destroying breast cancer cells. The 30-45 nm green gold nanoparticles were shown to have a spheroidal shape by scanning electron beam microscopy [45]. It is preferred to use particles smaller than 50 nm for anti-tumor applications [46]. The findings demonstrated that, despite not affect normal cells, gold nanoparticles efficiently suppressed the proliferation of breast cancer cells (HCF-7, Hs 578Bst, UACC-313, and Hs 319.T). When the extract content reached 10 weight percent, more anti-tumor activity was also observed in the biofabricated magnetite. Moreover, the IC50 values of the colon cancer cells were 99.8 μg/mL while the control cells were 140.8 μg/mL. [47]. Green nanoparticles demonstrated a great anti-tumor effect against several cancer cells very quickly, without damage. Thanks to this novel therapeutic strategy, there is now hope for a cure for this deadly illness. But most studies don't use in vivo experiments to demonstrate that these eco-friendly nanoparticles are potent anti-cancer drugs.

4.1.1 Types of Green Synthesized NPs in the Cancer Treatment

(a) Ag NPs: Ag NPs are a common target for nanoparticle research because of their anticancer properties. Ag NPs have demonstrated potent anticancer efficacy against a broad range of cancer cell types when they are synthesized sustainably

from a variety of plant materials. These cell lines include PC-3, HeLa, KB cells, Hep G2, L-132, MIA-Pa-Ca-2, MDA-MB-231, and prostate. These Ag NPs may eventually replace more conventional chemotherapy treatments. Ag NPs have historically been produced using a variety of plant compounds, including extracts from plants including Azadirachta indica, Carica papaya, Capsicum annuum, Salacia chinensis, and Artemisia vulgaris. Numerous cancer cell lines have shown these substances to be cytotoxic. Ag NPs produced from Carissa caranda have antioxidant qualities that make them a prospective candidate for application in cancer therapy and bioimaging. The water-based extract of citrus carandas contains a broad range of bioactive substances, such as proteins, enzymes, glycosides, alkaloids, flavonoids, phenols, tannins, and polysaccharides. Each of these substances has a function as a reductant and a scaffold during the biofabrication of Ag NPs [54].
(b) Au NPs: Biomedical imaging, pharmaceutical delivery, diagnosis, and treatment all make use of gold nanoparticles (AuNPs) [55]. Their ability to identify and completely eliminate cancer cells is remarkable. Since plant extracts are used in the environmentally friendly manufacture of AuNPs, their therapeutic efficacy has increased even further. A variety of plants can be used to produce AuNPs. Glycine max, Centella asiatica, Glyctanthes arbortristis, Cinnamomum zeylanicum, Rosa hybrida, Chrysopogon zizanioides, Abutilon indicum, Nerium oleander, Ocimum tenuiflorum, M. tenacissima, and Ocimum tenacissima leaf extract are an assortment of these species. The AuNPs had a noteworthy anticancer impact. Additionally, by conjugating AuNP surfaces to pharmaceutical and/or diagnostic chemicals, they can be functionalized for theragnostic applications.
(c) Iron oxide nanoparticles (IONPs): The usage of IONPs has grown significantly in the fight against cancer. These nanoparticles exhibit stability, surface alteration capability, and supermagnetic activity, which make them a promising tool with minimal side effects for enhancing tumor margin delineation. NPs supplied through the reticular endothelium system can also be used to scan macrophage-rich organs such as the spleen, liver, and bone marrow. Hordeum vulgare, Rumex acetosa, Sageretia thea, aloe vera, alfalfa, grape seed, brown seaweed, plantain peel, eucalyptus, Sorghum, Camellia sinensis, and other plant materials were needed to produce green-synthesized IONPs [61, 62]. They have demonstrated anticancer effectiveness against a number of cancer cell lines, and they may target particular areas while releasing medication.
(d) Titanium oxide nanoparticles (TiO_2NPs): Bioengineered TiO_2 NPs have been shown to exhibit hydrophilicity, electrical, optical, physical, and photocatalytic properties, in addition to oxidizing power [63]. These characteristics perhaps explain their crucial involvement in the prevention and treatment of cancer. Studies have indicated that they have the ability to specifically destroy cancer cells [64]. The Himalayan Polygonaceae herb Rheum emodi was used to generate TiO_2 NPs from its roots. Because it contains aloe emodi anthraquinones, emodin physician, and chrysophanol, this herb is well known for its therapeutic properties. These NPs protected healthy cells while destroying cell lines of liver cancer [65].
(e) Cu NPs: Cu NPs, or copper nanoparticles, have been shown to slow the growth of cancer cells. Biologically produced CuO NPs can prevent cancer angiogenesis by triggering cell death and exhibiting antiangiogenic effects on endothelial cells [66]. By inducing ROS-mediated cell death and lowering mitochondrial membrane potential, copper nanoparticles made from extracts of Ficus religiosa leaves shown anticancer effects. Other green CuO NPs that have been shown to exhibit anticancer properties include those made from the leaf extract of Acalypha Indica [67] and the fruit extract of P. nepalensis [68].
(f) Si NPs: Silica nanoparticles, or Si NPs, are widely regarded as safe and do not pose any hazard to living things. Olive residual ash was used to create Si NPs [68]. The cytotoxic effect was far more pronounced on breast cancer cells than fibroblast cells, with manufactured SNPs having far less detrimental effects on fibroblast cells than commercially accessible SNPs. Because plant-derived SiNPs are more hazardous to cancer cells than fibroblasts, they may find application in the treatment of cancer [69].
(g) Carbon-based nanomaterials: Carbon-based nanomaterials such as graphene oxide (GO), graphene quantum dots (GQDs), and carbon nanotubes (CNT) have garnered attention in the recent past for potential applications in cancer therapy. These materials have shown interest from the imaging, biosensing, and pharmaceutical administration domains. However, several investigations and reviews have demonstrated that CBNs created chemically are cytotoxic. Bioengineering CBNs from plants has thus far been the subject of considerable research. An assortment of plant materials, such as orange peel, Aloe vera, Trapa bispinosa, Jinhua bergamot, Sccharum officinarum, mulberry leaves, watermelon, and pomegranate skins, have been utilized in the environmentally friendly synthesis of carbon nanotubes. Anticancer properties have been observed in these nanotubes [70], and they have also been utilized to deliver anticancer medications in an efficient manner [71].

Environmentally friendly processes were used to make zinc oxide (ZnONPs) [73, 74], nickel oxide (NiONPs) [72], and magnetic nanoparticles (MNPs) [75]. All three compounds have shown promise in the treatment of cancer. For targeted drug delivery, therapies, and imaging, their unique properties are especially intriguing. Typically, the effectiveness of NPs is dictated by the hybrid of the particles' distinct properties and the plants' medicinal potential. Being careful to select the appropriate plant species, organs, extracts, or phytomolecules is essential because some plants may be toxic to certain cell types. On the other hand, cancer cell targeting should be combined with certain plant features. We can only hope to achieve anticancer efficacy in clinical and in vivo settings by delving further into the nanoscale system, metabolic and molecular mechanisms, and cellular signal pathways.

4.2 Antibacterial Effect

Hazardous bacteria pose a serious hazard to human health due to their ease of penetration into the human body. Another effect of overusing antibiotics is drug resistance, which makes treating a variety of infections more challenging. Thus, one objective of current research is to find antibacterial medications that work for these challenging conditions. Positive and gram-negative bacteria both appear to be inhibited in their growth by green nanoparticles, according to encouraging data. However, it's still unclear exactly how it stops bacterial growth and eliminates them. The shape, size, and surface area of nanoparticles are only a few of the attributes that greatly influence how they damage bacterial cells. By interacting with their walls or membranes or by entering their cells, the nanoparticles have the potential to kill the bacterial cells. Prunus dulcis was employed in the disk diffusion method to synthesize zinc oxide nanoparticles. Zinc oxide, which is around 25 nm in size on the nanoscale, appeared to be nearly perfectly round based on scanning electron microscopy (SEM) photographs. The agar diffusion method was used to further investigate the antibacterial properties of zinc oxide. The experimental data showed that zinc oxide had a beneficial antibacterial effect against gram-positive bacteria, with 18 mm inhibition zones on Staphylococcus aureus and 32–25 mm inhibition zones on Escherichia coli and Salmonella paratyphi, respectively. On the other hand, the antibacterial properties of zinc oxide did not suppress gram-negative bacteria such as P. mirabilis and K. pneumoniae [76]. Another study focused on the environmentally benign and chemically-based synthesis of zinc oxide from three green sources: rosemary, basil, and garlic. The testing results indicated that green zinc oxide had a stronger antibacterial impact than chemically produced zinc oxide. Furthermore, the as-fabricated zinc oxide from garlic, basil, and rosemary showed maximal zone diameters of 22.0 mm, 19.2 mm, and 22.0 mm when tested against S. aureus [77].

The antibacterial efficacy of Berberis vulgaris nanoparticles against Escherichia coli and Staphylococcus aureus was examined, as well as their silver content. This led us to conclude that silver nanoparticles were highly effective against both kinds of bacteria. Silver's ability to interact with thiol groups to impede bacterial respiration is a more important part of its antibacterial action. Moreover, because silver nanoparticles have a significant affinity to membrane cells that contain phosphate and sulfur, they can interact with bacterial cell membranes [78]. The antibacterial properties began to work when S. aureus and E. coli's cell membranes broke down. Furthermore, deoxyribonucleic acid-related activities that degrade DNA and produce reactive oxygen species contributed to the bacterial cell damage [79].

4.3 Antioxidant Effect

Naturally occurring or artificially produced antioxidants play a critical role in shielding biomolecules from the damaging effects of free radicals. This comprises proteins, carbohydrates, and nucleic acids. Natural compounds and endogenous sources are the two main categories into which you can divide these antioxidants. Whereas the latter comprises exogenous sources such as metal elements, vitamins, carotenoids, and polyphenols, the former comprises compounds such as enzymatic and nonenzymatic substances. Synthetic antioxidants include compounds containing polyphenols and nanooxidants [80]. There are many antioxidant mechanisms that depend on the quantity and position of active groups, one of which is reactive oxygen species scavenging. Additional ways that antioxidants work are through inhibiting enzymes, breaking down hydrogen peroxide and other peroxides, and chelating metal ions [81].
In one study, platinum nanoparticles were produced using Atriplex halimus for potential use in biology. High-resolution transmission electron microscopy images show the spherical, microscopic (between 1 and 3 nm) platinum nanoparticles that are produced by biosynthesis. The 1,1-diphenyl-2-picrylhydrazyl radical scavenging percentage, or DPPH, dramatically rose with exposure to these platinum nanoparticles, the study found. The DPPH scavenging percentage increased significantly to an amazing 72% at 50 mg/mL with a concentration of 12.5% platinum nanoparticles and an initial value of 13.8%. Additionally, A. halimus was reported to have 48.35% DPPH scavenging activity at a dosage of 50 mg/mL. The groups treated with A. halimus and platinum nanoparticles had higher scavenging percentages against DPPH than the vitamin C positive control group. A scavenging rate of 47.8% was obtained with 50 mg/mL of vitamin C [82].

Some intriguing results were found when researching Eucalyptus robusta's anti-DPPH properties and the zerovalent iron it biosynthesizes. Compared to pure Eucalyptus robusta, zerovalent iron nanoparticles were shown to have a higher scavenging capacity. Previous studies have assessed the extract's scavenging capabilities and that of bio-fabricated zerovalent iron, but their findings haven't always been in agreement [83]. It has been found in several studies that zerovalent iron nanoparticles have a scavenging activity that is either reduced or comparable to the original extract [84, 85]. Zerovalent iron nanoparticles had lower concentrations of polyphenols and flavonoids compared to the pure extract, even though these components aided in the reduction process that caused the nanomaterial to be produced. The zerovalent iron nanoparticles containing flavonoids and polyphenols may also act as stabilizing agents, which is even more significant.

4.4 Drug Delivery

For pharmaceutical compounds like proteins, enzymes, vaccines, and pills to function better, their drug delivery systems must be upgraded. Traditional drug administration techniques like solutions, emulsions, and suspensions require high dosages and have several drawbacks, such as decreased stability, less selectivity, and the potential for fluctuations in plasma drug levels. Thus, achieving targeted distribution that is neither easily cleared nor degraded has been a top priority. Medication delivery system improvements come in three main forms. The primary focus of the first generation was achieving sustained release through transdermal and oral delivery. The next generation's main focus was on using environmentally friendly nanomaterials. The third generation of pharmaceutical delivery systems addresses the physicochemical and biological restrictions [86]. The pharmacological delivery of loaded drugs with physiological pH, moisture content, and enzymes in nanosubstances is an interesting technique to treat many illnesses due to its regulated release, high bioavailability, targeted distribution, and preservation.

Silver nanoparticles enclosed in protein were stabilized using egg protein, leading to the development of a hesperidin-containing medicine delivery system. The protein-capped silver may provide a significant amount of hesperidin to the targeted cells, as evidenced by the 83.3% hesperidin loading rate. A successful drug loading was indicated by the free protein-capped silver's polydispersity index, which increased from 0.3 to 0.5 after hesperidin loading. Zeta potential measurements used in additional research showed that the free silver contained by proteins had a net charge of -18.5 mV. In contrast, a silver surface that had been loaded with hesperidin and protein-capped showed a transmitted charge of -0.2 mV. Hesperidin adds a net surface charge to the mixture due to the negatively charged groups in its molecules [87]. Another study looked into the synthesis of gold nanoparticles for use as zonisamide release vehicles using Juglans regia. When the zonisamide-gold nanoparticles and free zonisamide were compared, it was found that the free zonisamide released its zonisamide ten days faster than the zonisamide-gold system, which released its zonisamide more gradually. After 11 days, the proportion of total zonisamide released by the zonisamide-gold system was 76.2%, whereas the percentage of free zonisamide was 96%. This implies that zonisamide release may be facilitated by the zonisamide-gold combination as produced [88].

Silver nanoparticles made from Aesculus hippocastanum and their drug-release properties. First, by examining the FTIR spectra of the silver nanoparticles, the researchers were able to determine that they had bonded resveratrol. Furthermore, the zeta potential investigations' shifts from -12 to -34 Mv demonstrated that resveratrol's negative charge increased when it was linked to silver nanoparticles [89]. This shift in zeta potential verified that resveratrol and silver nanoparticles were conjugated. Next, we looked at the release profile of resveratrol. In the first thirty minutes, the release rate at pH 5.2 was 11.3%, while at pH 7.4, it was 8%. The percentages of release in 5 hours were 45.6% at pH 5.2 and 32.3% at pH 7.4. This result showed that resveratrol was released in an acidic environment at a substantially quicker rate, which is consistent with previous research [90]. Given that resveratrol releases quickly in an acidic environment, it is plausible that cancer cells can modify this release profile as a result of their acidic surroundings. Lastly, for a variety of medications, green nanomaterials have shown promising results for controlled release and drug-loading efficiency. Nevertheless, the lack of in vivo studies remains a barrier to their broader application in pharmacology.

5. Environmental Remediation

5.1 Soil Remediation

Ecosystems and human health are suffering as a result of the severe soil contamination issue, which has been getting worse for a while. Two of the various strategies used to address soil contamination are excavation and disposal as well as excavation and ex-situ treatment. However, these procedures are very costly, time-consuming, and hazardous. As a result, approaches like spreading nanoparticles throughout the ground that address the issue at its root have gained traction. Certain environmentally friendly nanomaterials can successfully remove toxins from soil, including heavy metals and dyes. This is because to their high mobility, huge surface area, low toxicity, and strong reactivity [91]. Typically, improving soil quality involves more than just soil remediation; other factors include (i) reducing soil aggregation, (ii) enhancing organic matter-containing soil, (iii) strengthening the nitrogen-phosphorus-potassium cycle, and (iv) boosting soil nutrition. A zerovalent iron nanocomposite with bentonite to remove chromium from polluted soil. The distinctive bands of polyphenols, including green tea, were visible in the Fourier transform infrared pattern, indicating green tea's dual role as a stabilizing and reducing agent. The results showed that soil treated with bentonite-green zerovalent iron released fewer chromium ions in comparison to the control. Additionally, there was a drop in the mobile fraction and an increase in the fractions bound to residue and oxide. These results demonstrated that the most efficient method for stabilizing and eliminating chromium ions from contaminated soils was a zerovalent iron nanocomposite including bentonite [92]. Additionally, by reducing cadmium ingress and enhancing nutrient delivery, biogenic copper nanoparticles lengthened and increased the biomass of wheat plants. Thus, rather than using remote techniques, copper might be utilized to lessen cadmium toxicity in wheat plants. While green nanoparticles have been proven to lessen heavy metal stress in numerous plants, more research is needed to understand the molecular pathways of nanoparticles in plants when they alleviate metal stress.

To prevent fungal infections in many kinds of cotton, bio-fabricated zinc oxide from Trichoderma harzianum was applied to soil pathogens such as Rhizoctonia solani, Macrophomina phaseolina, and Fusarium sp. The enhanced plant life, length, and weight in Giza90 indicates that zinc oxide's antifungal effects differed throughout cotton cultivars, and that 200 μg/mL of zinc oxide was very successful in managing disease. Zinc oxide at a concentration of 200 μg/mL increased plant survival in the Giza94 cultivar when compared to the disease-free control plant. However, the length and weight of the Giza94 cultivar shown notable responses to zinc oxide [94]. Zinc oxide made bio-from Streptomyces plicatus is also effective in controlling plant microbes. The experiment showed that Meloidogyne incognita could attain an amazing 96.7% mortality rate in just three days. Moreover, zinc oxide at concentrations ranging from 12.5 to 50 μg/mL improved

Vicia faba seed germination. Green nanoparticles are the best option for clearing contaminated soil, particularly for heavy metals including chromium, arsenic, nickel, and cadmium. These nanoparticles not only affect plant growth but also have antibacterial properties that work well against a range of plant illnesses [95].

5.2 Water Remediation

Water source contamination is a widespread and dangerous issue that puts Earth's ecosystems at jeopardy. Therefore, experts in environmental protection have been working nonstop to refine methods of water purification, including ozonation, adsorption, precipitation, and catalysis, to mention a few. When compared to other techniques, adsorption and catalysis are particularly good since they are simple to use, have little toxicity, and can be reused. They are very desirable options for wastewater cleanup because of these features. Green nanoparticles have shown to be effective adsorbents and catalysts when it comes to removing hazardous pollutants such as heavy metals, organic dyes, aromatic chemicals, and pharmaceutical residues.

Iron nanomaterial developed from Artocarpus heterophyllus for basic dye degradation of fuchsin. Based on X-ray diffraction studies, we successfully produced iron oxyhydroxide, hematite, and zerovalent iron. They broke down Fuchsin basic at a rate of 87.5% in the first 20 minutes using a mixture of iron and hydrogen peroxide, which is similar to Fenton degradation. The breakdown rate of 4.8% was much lower when hydrogen peroxide was used alone, without the presence of iron nanoparticles.

Acid blue-15 is broken down using an eco-friendly synthetic magnetite sono-Fenton reaction. The study indicates that there are multiple pathways through which hydrogen peroxide can be activated to generate hydroxyl radicals: the homogenous Fenton process, which is sparked by leached iron ions; (ii) the redox reaction between iron ions, $Fe2+/Fe3+$; (iii) the splitting of hydrogen peroxide by ultrasonic waves; and (iv) the creation of hydroxyl radicals through the splitting of water. After attacking acid blue-15 with precision, the resulting hydroxyl radicals created intermediates, which sparked a chain reaction that produced carbon dioxide and water [96].

Methylene blue can be adsorbed by magnetite nanoparticles derived from Jengkol. In proportion to the Jengkol extract volume (from 5 to 15 mL), the magnetite particle size decreased. The reason for this is presumably that Jengkol's high phenolic content functions as a capping agent, keeping the particles from aggregating. The magnetic of pure magnetite was found to be stronger than that of Jengkol magnetite, as determined by means of a vibrating sample magnetometer. The saturation magnetization values were 68.4 emu/g, in particular, when 5 mL of extract was utilized to evaluate pure magnetite. Analyzing Jengkol-derived magnetite with 15 mL of extract yielded findings of 25.6 emu/g. According to the Langmuir model, the magnetite from Jengkol, when treated with 5 mL of extract, had an estimated adsorption capacity of 68.5, and when treated with 15 mL of extract, it increased to 65.4. Magnetite made from Jengkol was adsorbed with methylene blue mostly by hydrogen bonding and electrostatic interactions [97].

After zirconium oxide was produced by pseudomonas aeruginosa, tetracycline was extracted from wastewater. Peak tetracycline removal efficiency of zirconium oxide was reached at pH 6, with a pH increase of more than 98%. That's because there are three different types of tetracycline: zwitterionic (pH 3.3 to 7.7), anionic (pH 7.7 or higher), and cationic (pH 3.3 or lower). With a 7.2 point of zero charge, this indicates that electrostatic interactions between the positively charged zirconium oxide and the zwitterionic tetracycline are expected. Comparing zirconium oxide to other pertinent green adsorbents, it demonstrated exceptional adsorption performance. The highest adsorption efficacy reached 526.32 mg/g in a mere 15 minutes, which is rather impressive. Additionally, zirconium oxide showed excellent recycling properties; even after five cycles of use, it retained an 81.6% removal effectiveness [98].

6. Significance of Green Synthetic Routes

Microbes are preferred over plants in the synthesis of nanoparticles (NPs) [99]. The second approach is not practical since it calls for more exacting aseptic conditions, a more involved procedure, and a longer incubation period. Environmentally friendly synthesis of metal nanoparticles, like gold and silver, is an intriguing new area in nanotechnology. It has become more and more common because it is less risky than chemical hazards, affordable, and environmentally friendly. When it comes to creating nanoparticles, green synthesis has numerous advantages over other methods, including being safer for the environment, having a high yield, being simple to synthesize, using less expensive and toxic solvents, and taking less time [100]. They require less power overall and perform well at mild temperatures. This claim states that plant-made silver nanoparticles are more biologically active than those produced using traditional chemical methods.

In green synthesis, a one-pot reaction is typically used since it is straightforward and simple to set up [101]. It is scalable and has improved biocompatibility with healthy tissues for in vivo applications. Dangerous substances are also eliminated. Other metallic nanoparticles have several possible biological and industrial applications, and this procedure is also reasonably priced. Green-generated metal nanoparticles have been extensively researched for possible uses. A selection of the most important components supporting green synthesis are shown in Figure 3.

Fig. 3: Significance of Green Synthesis

Conclusion

In conclusion, the exploration of green synthesis methods for nanoparticles and their multifaceted impact on biomedical and environmental domains showcases a promising avenue for sustainable technological advancement. Green synthesis techniques offer eco-friendly alternatives to traditional chemical methods, harnessing natural resources and reducing environmental harm. The significant potential of green-synthesized nanoparticles in biomedical applications, including drug delivery, imaging, diagnostics, and therapy, underscores their pivotal role in advancing healthcare technologies. Simultaneously, their applications in environmental remediation, such as pollutant degradation and wastewater treatment, demonstrate their efficacy in addressing pressing environmental challenges. By leveraging the unique properties of nanoparticles and adopting sustainable synthesis approaches, we can contribute to both improved healthcare and environmental sustainability. However, challenges such as scalability, reproducibility, and regulatory considerations remain to be addressed. Future research efforts should focus on optimizing green synthesis techniques, elucidating their mechanisms, and exploring novel applications to realize the full potential of green-synthesized nanoparticles. Ultimately, the integration of green nanotechnology into biomedical and environmental sectors holds promise for fostering a healthier, greener, and more sustainable future.

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