**PLANT BASED GREEN SYNTHESIS OF NANOMATERIALS**

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**ABSTRACT**

Nanotechnology and biomedical science have opened up a wide range of biological research areas and medical applications at the molecular and cellular level. The biosynthesis of nanoparticles has been proposed as an alternative to chemical and mechanical processes that is both economically and environmentally feasible. The green chemistry method of plant-mediated nanoparticle production connects nanotechnology and plants. Therefore, it is anticipated that new, inexpensive, pH-neutral, and ecologically benign technologies for creating nanoparticles will emerge. With these goals in mind, various techniques for nanomaterial production were used. When it comes to biologically based alternatives, plants and plant extracts appear to be the best available choice. The natural world's chemical factories are plants. They are inexpensive and require little upkeep. Nanotechnologies' benefits and drawbacks may be readily quantified. The purpose of this study is to look at the variety of the area, starting with the history of nanotechnology, the characteristics of nanomaterials, the various synthesis techniques, the numerous benefits and drawbacks of various approaches, and their use.

**Keywords**— green synthesis; nanoparticles; plant extracts; phytochemicals; biogenic nanoparticles; antimicrobial activity; mechanisms of action; biocompatibility; biomedical applications.

1. **INTRODUCTION**

Over the past few years, nanotechnology has received a lot of attention. Materials with a thickness between 1 and 100 nanometers fall within the category of nanotechnology. Although the size of the compound defines its classification as a nanomaterial, its shape and geometry have a significant effect in its features. Nearly every industry, including but not limited to: agriculture, electronics and medical, uses nanoscale materials. Materials for use are being revolutionized by nanomaterials thanks to advances in nanotechnology, which have significantly improved their thermal, mechanical, and barrier qualities [1]. Different nanoparticle morphologies, such as rods, spheres, quantum dots, or particles, provide the potential to produce a wide range of applications and unlimited chances for technological advancement [2]. 0D and 1D nanomaterials are used in numerous industries and fields. Electronics make significant use of Nano sheets, which are mostly made of 1D nanomaterials that can be highly conductive and sensitive. Drug delivery uses nanoparticles, a type of 0D nanomaterial, effectively. Nanoparticles are largely used in the distribution of SARSCoV2 vaccinations. The longest 1D nanomaterials that can alter their thickness for any particular use are nanoparticles. For bio imaging, single walled carbon nanotubes can be utilized to target particular organs and generate a fluorescent signal that is strong enough to be recognized [3]. Additionally, Bucky balls and quantum dots have a significantly different composition from nanoparticles. They are useful for laser applications in addition to other things because they are smaller than an atom and generate light when stimulated [4].

1. **PHYSICAL TRAITS OF NANOPARTICLES**

The enormous surface area of nanoparticles makes them special, and the contribution of the little bulk of the substance is dominated. There are several various colors for nanoparticles, including, yellow, gold, and grey. In comparison to the gold slabs (1064°C), the gold ones melt at much lower temperatures (around 300°C for 2.5nm size) [5]. Silver nanoparticles in particular have unique physio-chemical characteristics, such as high thermal and electrical conductivity, surface enhanced Raman scattering, chemical stability and catalytic activity, and nonlinear optical behavior, which makes them significantly more effective than thin films in absorbing solar radiation in photovoltaic cells. Since the particles are smaller, continuous sheets of bulk material absorb more solar light [6].

1. **CHEMICAL TRAITS OF NANOPARTICLES**

Nanoparticles typically have a low melting point and a lower lattice constant because of the shift in the surface energy to volume energy ratio. The melting point of nanomaterials will drop as their size decreases. The surface energy increases as the surface area does. According on the degree of interaction between particles and matrix, the melting point for nanomaterials may be low or high [7].

1. **SYNTHESIS OF NANOMATERIALS**

Although there are numerous methods for creating nanomaterials, bottom-up and surface-based synthesis are the two most common. Both of them use larger materials to divide them into Nano sized particles, whereas the other creates huge nanomaterials by using individual atoms. Iron oxide (Fe3O4), cadmium sulfide (CdS), lead sulfide (PbS), selenium (Se), and gold (Au) are examples of metal nanomaterial products which possess important characteristics for a variety of applications [8].

Methods for top-down or bottom-up synthesis. There are two methods for creating nanomaterials. The method of dissolving large materials into monomers is known as top-down synthesis. Laser ablation is an illustration of a top-down synthesis technique. When atoms are combined with another substrate and can be transformed into a desired nanomaterial, the process is referred to as bottom-up synthesis. Reactions can be triggered by any external force, such as a hydrothermal synthesis that introduces volatile substances, like chemical vapor deposition.

There are two basic types of nanomaterial synthesis: conventional methods and environmentally friendly ways. Using traditional methods for nanomaterial fabrication has a number of attractive benefits. These techniques generate a wide range of nanoparticles with numerous applications. Certain approaches are providing wide Scalability and strict control of Nanoparticle Morphology, with applications in innovative battery conduction, electrical applications, treating diseases, and energy storage conservation [9].

**V. TRADITIONAL SYNTHESIS METHODS**

The creation of nanoparticles and nanostructured materials is accomplished using traditional methods for synthesis of nanomaterials. While these approaches are frequently simple and have been successful, they could not offer the exact control and scalability that more sophisticated methods do. Here are a few typical conventional techniques for creating nanomaterials [10]:

1. **Sol Gel Synthesis**

Sol Gel synthesis is a usual technique to produce nanomaterials. This relatively simple approach can be used widely in the synthesis of nanomaterials, for instance using a number of other metal oxides as TiO2, SnO2, ZnO, Fe2O3, WO3 in addition to silicon and platinum. The hydrolysis of precursors using either water or an organic solvent is the first step in this process, which is typically carried out in five phases. The molecules that are linked to one another then start to create connections as the process moves onto the Condensation stage. The resulting "gel" is then developed and dried by either supercritical, cold or hot drying, each of which yields slightly different results. Calcination must be done in order to get rid of the leftovers and dry the water that is still there [11].

Sol gel-produced nanomaterials offer a wide range of uses, including medicine delivery, waste water treatment, construction materials, and several sensors. This approach can be used in an industrial setting because to the little amount of ingredients required to make the end product. Additionally, synthesis can only proceed and increase in attractiveness by employing a single Gel Pot.

Although the Sol Gel synthesis method has several advantages for producing nanomaterials, it has some drawbacks for safeguarding the environment and public health. First of all, there is a significant risk that the synthetic solvents used to dissolve nanomaterial precursors will have harmful effects on human health and the environment. These solvents can influence a range of biological systems, including those used in neurotherapies or reproduction. The technique, while efficient and successful, comes with a number of hazards that must be overlooked [12].

1. **Chemical Vapor Decomposition**

In general, a substrate can be produced through the deposition of chemical vapors. One or more volatile compounds are given a metal, such as, Zinc, Iron or Nickel, which reacts with the substrate to create a final 2D product. The reactions between a substrate and a volatile molecule take place in a vacuum at a high temperature with the help of N2 gas and frequently a catalyst [13]. The temperature, substrate, and precursors can all be altered to yield products with different morphologies, sizes, and geometries. Carbon nanomaterials are another illustration of the level of control that a scientist has over the final product generated via CVD. Graphene, carbon nanotubes, fullerene, and diamond-like carbon film nanostructures are a few examples of materials that can be created using CVD synthesis [14].

Due to the wide diversity of nanostructures that may be created by CVD, nanomaterials have also been applied in a number of different fields. There are a variety of intriguing and unusual applications, even though the bulk of nanomaterials made using other synthesis methods are also used in these applications. A few teams have been creating graphene glass using various CVD processes for the past ten years. This graphene glass can be used in a variety of applications, in addition to transparent electrodes, touch panels and windows. Nanomaterials can also be created via CVD by using semiconductors, nanotechnology sensors, conductive electrodes, and optics.

There are many variations on the traditional approach that are used in the current procedure for making nanomaterials, and each one entails dangers. One such risk that is also addressed by this slightly different technique is the usage of volatile gases and vapors. Although the gas or vapor in and of itself is not necessarily toxic, the side products created as a result of the reaction with the catalyst or substrate are frequently harmful to the environment as well as the person performing the synthesis. Plata et al. found that the synthesis of carbon nanotubes produces more than 45 distinct chemicals. Despite how unsettling these side effects are, they do not represent the primary risk connected with this approach. Vacuums need a lot of energy to be heated to their final temperature of 10,000 C for CVD synthesis [15].

1. **Hydrothermal Synthesis**

This includes solvothermal synthesis, commonly known as hydrothermal synthesis. The name given to methods that can make use of a substance's solubility by putting it inside of it. Crystal structures are produced as a result of hot water and high pressure. Before running it for a predetermined amount of time, a steel autoclave must be used to combine the products, precursors, water or any other solvent, and stabilizing agents. In order to change morphology, size, and geometry, the person operating the autoclave has the ability to change the precursors, temperature, and pH level of the solution [16]. Following this autoclave cycle, the items are cooled to ambient temperature before being later cleaned and dried.

Structures created by hydrothermal synthesis are used in a variety of industries, similar to other methods of synthesis for nanomaterials. The use of the materials is mostly reliant on their size, morphology, geometry, and surface coatings. The creation of elements for Na-ion and K-ion batteries is one of the more intriguing applications for hydrothermal synthesis. In particular, a wide range of nanostructures, including Nano rods, nonconductive nanowires, etc., as well as nanomaterials for electrode arrays in batteries, have been synthesized using the hydrothermal approach. Nanomaterials created using hydrothermal synthesis can be applied in a variety of different fields outside electrical ones, including healthcare, sensing technology, and electric media storage. The application of nanomaterials made from hydrothermal sources has been thoroughly reviewed by Darr et al., who have put more of an emphasis on this subject [17].

Hydrothermal synthesis is significantly cleaner and more energy-efficient when compared to other nanomaterial synthesis techniques; this is largely because of usage. The autoclave's lower temperatures this method does not quite correspond to the 12 principles of green chemistry, but it is moving in the right direction for mass production of nanomaterials. Caramazana et al. have reported the hydrothermal procedure. In comparison to the 543 kg of CO2 per kilogram of Ag2S nanoparticles produced by flame spray pyrolysis, the synthesis produced 10.86 kg CO2 per kg of Ag2S nanoparticles [18].

1. **Ultrasound Synthesis**

Ultrasound, sometimes known as sonochemistry of nanomaterials, is a typical laboratory technique used in the production of goods. By adjusting the sonic waves, this method causes cavitation, which in turn triggers chemical processes that result in the formation of nanomaterials. Cavitation is the process by which ultrasonic energy is rapidly stored in a liquid by tiny bubbles, which then expand and burst, releasing the energy back into the surrounding space. The cavitation event is constrained for a relatively brief time and produces intense heat (10,000 K) and pressure (1,000 Bar). A cavitation event causes interactions. Additionally, a chemical reaction with a precursor found in the environment can also produce the final nanomaterial. The precursor liquid, in which the nanomaterials react with ultrasonic waves, can be changed to regulate the size and shape of the final products that are produced [19].

What can be applied to a nanocomposite depends on its precursor; transition for instance, metal carbide is a highly effective technique for producing nanoparticles that are employed in chemical manufacturing and for uses like magnets. Nanoparticles with the mo2C and w2C catalyst for hydro dehalogenation are highly efficient catalysts that keep our bodies and environment safe from dangerous chlorofluorocarbons, as well as some of the more toxic Halogenated Organic Chemicals. In various applications, including drug delivery, synthetic nanomaterials are also capable of being used as magnets. Local magnets are placed in the place where the drug is needed to take the medicine into the human body by attaching it to a magnetic nanoparticle [20].

One of the greenest ways to create "traditional" nanomaterials is by ultrasound/ sonochemistry, which uses little to no toxic chemicals or organic solvents. . Moreover, there is a low amount of energy required to produce ultrasonic waves. Further, compared to other technologies like flame spray pyrolysis & Sol-Gel synthesis, the energy needed to produce ultrasonic waves is negligible. We are currently researching a large-scale ultrasonic synthesis that doesn't need catalysts from chemicals because the scalability of the ultrasonic approach is one of its limitations. Recent research by Hujjatul Islam and his associates has demonstrated the capability of the ultrasonic one-ton pot synthesis process to create large quantities of nanoparticles. The occurrence is just one in a string of occasions that allow for the common synthesis of nanomaterials [21].

1. **Laser Ablation**

The technique of breaking down bulk materials into their smaller constituents through the use of laser pulses is known as laser ablation. The components liberated during the ablation must be reduced to nanoscale size and gathered as a finished good. This procedure is carried out in a gaseous or liquid medium to ascertain the size and shape of such nanomaterials. In gas or a vacuum, the nanomaterial collects as a thin layer on a surface. However, when done in a liquid, a colloidal structure is produced. By varying the pulse length, laser's power, and wavelength, the user can also change the size and shape of the finished object. The ability of the laser to further "fine tune" the shape and size of the nanomaterial gives the operator a significant level of control over the final output.

In recent times, it was discovered that a range of disorders, including certain types of cancer, can be treated with laser-ablated nanomaterials. In order to identify human prostate tumors, Walter et al. used conjugated aptamers and AuNP created by laser ablation in Tris’s buffer [22]. Furthermore, Salmaso et al. discovered that human breast cancer may be detected in culture using laser-ablated AuNP with a thermoresponsive polymer coating. Beyond the treatment of cancer, laser-ablated nanomaterials have applications in imaging, bio sensing, luminous semiconductors, and seed germination using nano fertilizers [23].

Although laser ablation can be utilized in an eco-friendly manner, it frequently works in conjunction with organic solvents to further regulate the product's shape, which is frequently the case for a range of metal nanoparticles. The use of organic solvents poses a risk to the user as well as to the environment, as was already mentioned. Additionally, laser ablation—one of the most energy-intensive processes for producing nanomaterials—has an adverse impact on the environment since the electricity required to power the laser is typically generated from coal or gas [24].

1. **Flame Spray Pyrolysis**

Flame spray pyrolysis (FSP) produces nanomaterials by mixing a high enthalpy precursor (usually an organic solvent) with oxygen and hydrocarbons in a flame. These parts combine to create nanomaterials, which then go through a filter and collect on a substrate. The size, shape, and morphology of the final product can be controlled by modifying the oxygen level, precursor, and temperature through the number of hydrocarbons released into the environment. One of the most important elements in creating the required nanomaterial is the choice of precursor. To create a uniform morphology of nanomaterials, it is necessary to use precursors with high enthalpies and low melting temperatures; alternatively, (in the absence of fine-tuning the manufacturing conditions), the end products will be a heterogeneous combination of nanomaterials that are mostly useless. The interior of the furnace may become as hot as 2800 K during this procedure, putting the person(s) operating it in danger. This approach is both industrial-scale and scalable [25].

The creation of nanoparticles is caused by flame spray pyrolysis. A precursor (usually an organic solvent) breaks down into its monomers in the complex procedure called "flame spray pyrolysis," which is then accelerated by very extreme temperatures in order to react with hydrocarbons. The resultant nanoparticles are collected on a substrate. Despite the fact that FSP can be scaled up to industrial levels, it is quite risky and its carbon dioxide by products significantly contribute to greenhouse gas emissions.

Over its extensive history, FSP has found diverse applications across various domains. Notable examples include the utilization of catalysts, such as TiO2 and ZnO-based photocatalysts, Au/TiO2 catalysts for CO oxidation, and Pt-Sn/Al2O3 catalysts for dehydrogenation processes. Moreover, the innovation by Eckert et al. has unveiled a cost-effective route for producing metal oxides through FSP, pivotal for laser technologies.

Beyond its role in catalysts and lasers, the realm of FSP-fabricated nanomaterials extends to encompass energy conversion and storage, solar cell technologies, and the degradation of dyes. However, it's undeniable that the process of creating nanomaterials through FSP carries inherent risks and hazards. Eckelman et al. have demonstrated that when compared to hydrothermal methodologies, FSP results in more than 50 times the carbon dioxide emissions. The diverse techniques employed in FSP synthesis can engender detrimental consequences for both human health and the environment [26].

An essential aspect of FSP involves the combustion of hydrocarbon fuels to generate the requisite conditions for nanomaterial production. This combustion produces carbon dioxide, a primary contributor to the greenhouse effect. Additionally, FSP often relies on organic solvents to contain precursors, which can pose significant risks to environmental integrity and human well-being.

However, it is indisputable that the utilization of these traditional methods carries a pronounced adverse impact. The extensive reliance on organic solvents within the nanomaterial synthesis process poses substantial risks to neurobehavioral and reproductive health. Moreover, the application of high-pressure and high-temperature conditions could exacerbate precarious working environments. A particularly concerning outcome of these syntheses is the excessive generation of carbon dioxide and volatile vapors, both potent contributors to the exacerbation of the greenhouse effect. Collectively, these procedures entail inevitable hazards for both the environment and the scientists engaged in the synthesis endeavors. The detriments associated with employing conventional techniques for nanomaterial synthesis far outweigh their merits.

Consequently, these factors have precipitated a waning interest in conventional synthesis methods, thereby ushering in the era of green synthesis. The conception and implementation of pioneering, forward-looking techniques that align with the principles of Green Chemistry are imperative, particularly given the ongoing climate crisis.

1. **Green Synthesis**

Utilizing an environmentally sound, secure, cost-effective, and ecologically conscious approach, green synthesis facilitates the creation of nanomaterials. This method harnesses microorganisms such as bacteria, yeast, fungi, algal species, and select plants as foundational elements. Distinct active molecules and precursors, including metal salts, dictate the ultimate morphology and size of the resulting nanoparticles. Additionally, green synthesis endows nanomaterials with valuable attributes such as antimicrobial properties, natural reduction capabilities, and stabilizing effects. These properties, which have only recently come to light following the publication of the comprehensive nanomaterials review by Saratale, R., et al., are attributed to the dynamic molecules within microorganisms utilized in the green synthesis process. Notably, enzymes, amino acid groups, proteins, and specific chemical structures are recurrently found in the components of these green entities, thus playing a pivotal role in the synthesis of nanomaterials [27].

1. **GREEN SYNTHESIS AND CHARACTERIZATION OF PLANT- DERIVED NANOPARTICLES**

The concept of "green synthesis" has been effectively realized through the utilization of fungi, algae, bacteria, and plants. Remarkably, diverse plant components such as leaves, fruits, roots, stems, and seeds have all found application in the creation of various types of nanoparticles (NPs). This approach enables the tailored production of NPs possessing specific dimensions, configurations, and compositions by leveraging plant extracts. Furthermore, a range of phytochemicals present within these extracts can play dual roles as both organic stabilizing and reducing agents during NP fabrication. Notably, plant-derived nanoparticles are widely acknowledged for their diminished potential to induce adverse effects in comparison to chemically synthesized counterparts. These biologically sourced NPs exhibit significant potential across domains like agriculture, food science and technology, bioengineering, cosmetics, nanomedicine, and human health safeguarding [28].

1. **TYPES OF PLANT BASED NANOPARTICLES**

The exposition encompasses the synthesis, characterization, and diverse applications of plant-derived nanoparticles (NPs) across various categories. Of these, plant-based silver nanoparticles (AgNPs) stand out as one of the most straightforward to fabricate. The green synthesis of AgNPs necessitates a solution containing silver metal ions and a biological agent with reducing properties. Employing an amalgamation of biomolecules like polysaccharides, vitamins, amino acids, proteins, phenolics, saponins, alkaloids, and/or terpenes to both reduce and stabilize silver ions, thus generating AgNPs, emerges as the simplest and economically viable approach. Notably, this method is applicable across a wide range of plant species, each harboring the potential for AgNP synthesis [29]. Gold nanoparticles (AuNPs) have garnered substantial attention due to their facile synthesis, ease of surface functionalization, and distinctive attributes, including their remarkable potential for medical applications, minimal toxicity, and high biocompatibility. Biogenic complexes encompass an array of chemical molecules that serve as effective reducing agents in the creation of AuNPs by precipitating gold metal ions, consequently leading to nanoparticle formation. Certain studies underscore the pivotal role played by biomolecules such as proteins, flavonoids, and phenols in metal ion reduction and the subsequent encapsulation of AuNPs within plant extracts [30]. Recent years have witnessed heightened interest in zinc oxide nanoparticles (ZnONPs) owing to their versatile applications in biomedicine, cosmetics, optics, and electronics. A multitude of investigations have been dedicated to the synthesis and utilization of ZnONPs via plant sources, microorganisms, and other organisms. The economical, safe, and uncomplicated synthesis processes associated with these nanoparticles have garnered considerable research attention. Various components of plants, encompassing flowers, roots, seeds, and leaves, serve as viable sources for generating ZnONPs. Remarkably, these nanoparticles exhibit a substantial bandgap of 3.37 eV and a notable exciton binding energy of 60 meV, imparting a range of semiconducting properties [31]. Copper nanoparticles (Cu NPs) have been successfully synthesized through the reduction of aqueous copper ions using diverse plant extracts. Copper (Cu), an economically viable metal, offers a more budget-friendly alternative compared to gold (Au) and silver (Ag). The formation of these nanoparticles is marked by the distinct presence of a 578-nm peak observable on UV-visible spectrometry. Despite this, apprehensions regarding their biosafety remain prevalent [32]. Furthermore, the array of metals extends to include nickel (Ni) and manganese (Mn). Beyond these, several additional metals like titanium (Ti), palladium (Pd), cerium (Ce), and platinum (Pt) have emerged as recent contenders for the creation of plant-derived nanoparticles, catering to an array of applications in both the biomedical and industrial realms.

1. **PLANT DERIVED NANOPARTICLE’S APPLICATIONS**

With their versatile applications spanning industries, electronics, environmental domains, energy sectors, and notably in biomedicine, nanoparticles (NPs) are currently witnessing substantial commercial demand. Among these, the extensively studied NPs encompass the renowned silver (Ag) and gold (Au) variants, exhibiting significant potential within the realm of biology-related applications. Notably, plant-derived green nanoparticles often exhibit fewer adverse effects on human health compared to chemically synthesized counterparts. Moreover, these environmentally sourced NPs offer an expansive array of potential applications, encompassing but not confined to the following:

* **Nanomedicine & Human Health:** Within the realm of nanomedicine and safeguarding human health, nanoparticles play a pivotal role. They exhibit a spectrum of attributes, including antimicrobial, antiparasitic, and antiproliferative properties. These characteristics, along with their potential for pro- or anti-apoptotic and pro- or anti-oxidative effects, are context-dependent. Additionally, nanoparticles contribute to anti-inflammatory activities, contributing to their significance in maintaining well-being.
* **Agriculture:** In the agricultural sector, nanoparticles hold significant relevance. They facilitate precision farming by enabling controlled release of agrochemicals, targeted delivery of biomolecules to specific sites, enhanced uptake of nutrients, and effective identification and control of plant diseases. These attributes collectively contribute to advancements in agricultural practices.
* **Bioengineering:** In the field of bioengineering, nanoparticles play a key role in various applications, including biocatalysts, photocatalysts, and biosensors. Additionally, they have substantial implications in the domains of food science and technology, influencing processes related to food processing, storage, and packaging.
* **Cosmetics:** Cosmetics leverage nanoparticles in an array of applications, including the formulation of sunscreens, anti-aging products, aids for hair growth, delivery systems for bioactive compounds, and the creation of nano-emulsions. These nanoparticles contribute to innovative solutions within the realm of beauty and skincare. The current special issue delves into the synthesis of copper nanoparticles (CuNPs) and nanoparticles derived from algae, casting a spotlight on two relatively lesser-explored yet impactful facets of green plant-based nanotechnology tools and techniques [33]. Algae, abundant in secondary metabolites that serve as both reducing and capping agents, emerge as unequivocal frontrunners for the environmentally friendly synthesis of nanoparticles. Their vast potential spans various domains, encompassing not only antimicrobial and anticancer properties but also extending to antifouling, bioremediation, and biosensing applications. Interestingly, despite their richness in attributes, algae had not received the same level of attention in the early stages of research on green NP synthesis using plant extracts, unlike their terrestrial counterparts in the realm of medicinal and aromatic plants. However, the challenge of upscaling for commercial utilization remains due to the nascent stage of development in this field. Copper (Cu), a relatively cost-effective metal, holds an economic edge over its counterparts, such as gold (Au) and silver (Ag). CuNPs have been successfully synthesized by reducing aqueous Cu ions through a diverse array of plant extracts. In a comprehensive and contemporary review by Letchumanan et al., the synthesis, therapeutic applications, and mechanisms of plant-mediated Cu/CuO (copper oxide) NPs are thoroughly explored. While Cu/CuO NPs offer several therapeutic benefits, it's imperative to acknowledge their potential toxicity towards healthy human cells and vital organs, a concern that could yield significant adverse repercussions. Hence, a meticulous investigation into the potential toxicity becomes imperative before integrating these NPs into medical applications. The review delves into a comparative analysis of these NPs' effectiveness in both in vitro and in vivo research, juxtaposed against commercial NPs, while also dissecting their toxic attributes. Furthermore, the potential of plant-based Cu/CuO NPs as a treatment avenue for diverse conditions like microbial infections, cancer, wound healing, and inflammation is elegantly elucidated through this review.

1. **Anti-cancer potential**

Nanomedicine embodies the utilization of nanotechnology to address a diverse spectrum of ailments, encompassing cancer, by means of prevention, detection, and treatment. It encompasses comprehensive strategies and effective approaches for combatting cancer, spanning diagnostics, prevention, treatment, and the potential for tailored therapeutic interventions. Numerous nanoparticles (NPs) sourced from plants exhibit potential efficacy against cancer cells. Notably, ZnONPs derived from Cassia auriculata leaf extracts have exhibited tumoricidal effects on MCF-7 breast cancer cells while sparing healthy MCF-12A human breast cells from adverse impacts. Similarly, green gold nanoparticles (AuNPs) synthesized from Trachyspermum ammi seed extracts demonstrated the ability to inhibit the proliferation of HepG2 cancer cells in a concentration-dependent manner. This effect was linked to a ROS-driven cell death mechanism. Recent investigations have unveiled a potential association between the disruption of mitochondrial membrane potential caused by plant-based NPs and their impact on mitochondrial function, possibly mediated through ROS-induced Caspase-3 gene expression and enzyme activity [34].

To comprehensively comprehend the outcomes of nanoparticles (NPs), a profound understanding of the molecular mechanisms underpinning their actions against cancer cells is imperative. Pertinent inquiries encompass the duration of NP persistence in the body, factors influencing their degradation timeline, strategies to prolong or shorten their persistence, both short-term and long-term effects, micro and macro-level bodily responses, and the establishment of standardized NP protocols for reproducible experimentation. These concerns demand resolution before integrating nanotechnologies into the healthcare domain.

Furthermore, a host of issues necessitate further exploration and testing. Scrutinizing potential risks associated with nanomaterials becomes essential to avert inadvertent consequences. Moreover, meticulous development of numerous nanomedicines and nano formulations, precisely targeting specific cancer cells, becomes pivotal to achieve the utmost safety and efficacy in therapeutic regimens. In summation, there is a sanguine aspiration that nanotechnology will expedite the advancement of more potent cancer treatments, equipping researchers with formidable tools to navigate challenges prevalent in the realm of medical research.

1. **Anti- leishmanial potential**

Leishmaniasis, a protozoan vector-borne disease, afflicts nearly 350 million individuals globally. Initially treated with chemotherapy drugs, these approaches brought forth unfavorable side effects. Notably, diverse nanotechnology-based strategies and products have emerged as potent anti-leishmanial interventions. These encompass liposomes, lipid nano-capsules, metallic and metal oxide nanoparticles, polymeric nanoparticles, nanotubes, and nanovaccines. These solutions capitalize on distinctive attributes including enhanced bioavailability, diminished toxicity, targeted drug delivery, and biodegradability. Interestingly, in the context of combating Leishmania amazonensis, the effectiveness of nanoxylan, synthesized through a green method utilizing corncob xylan as a reducing and stabilizing agent, came to the fore. While xylan in isolation exhibited no impact, the xylan-incorporating AgNPs showcased inhibitory effects on the viability of Leishmania amazonensis promastigote. This groundbreaking work underscores the potential of nanoxylan as a novel and promising class of antiparasitic agent [35].

1. **Anti-microbial potential**

One of the most pressing challenges in recent times is the escalating concern of antibiotic resistance, a predicament anticipated to intensify further. The rapid genetic evolution of bacteria has led to their increasing resistance to antimicrobial agents. In this context, biogenic nanoparticles (NPs) have exhibited promising outcomes in addressing multidrug-resistant bacteria, offering a potential avenue in the battle against these recalcitrant pathogens in the pursuit of novel therapies. NPs, alongside various organic and inorganic compounds, have been amalgamated into conjugates to bolster the antimicrobial efficacy. Silver (Ag) has long been recognized for its prowess in combatting diverse bacterial strains. Particularly noteworthy are green AgNPs synthesized from a Carissa carandas leaf extract, showcasing commendable antibacterial performance against various human pathogenic bacteria. Among them, Gram-negative bacteria, notably Shigella flexneri responsible for shigellosis, displayed enhanced susceptibility. Similarly, nanostructures combining palladium and silver (Pd-Ag) coated with reduced graphene oxide, produced via a stevia leaf extract, exhibited inhibitory effects against Gram-negative bacterium Escherichia coli. Inhibiting multidrug-resistant Pseudomonas aeruginosa and Acinetobacter baumannii, causative agents of ventilator-associated pneumonia, were the AgNPs derived from Saudi Arabian desert plant Sisymbrium irio. Furthermore, the antifungal potential of nanoxylan, derived from corncob xylan, was evidenced against Candida albicans, Candida parapsilosis, and Cryptococcus neoformans. Similarly, AgNPs sourced from the leaf extract of Clerodendrum inerme exhibited dual actions, both antibacterial and antifungal, targeting an array of human pathogenic strains [36]. Notably, AuNPs synthesized from the same extract of C. inerme exhibited comparable inhibitory capabilities. The authors postulate that the synergistic impact of bioactive phytochemicals absorbed from this plant possibly contributed to enhancing the antimicrobial potential of these NPs. Conversely, AuNPs derived from a T. ammi seed extract displayed limited antibiofilm effectiveness against Listeria monocytogenes and Serratia marcescens, potentially attributed to intracellular reactive oxygen species (ROS) generation. Similar vigor is observed in other metallic NPs with potent antimicrobial attributes, including antibiofilm qualities. An illustration is found in CuONPs originating from Cymbopogon citratus, which display robust antibiofilm properties. Intriguingly, the authors discerned variations in antibiofilm activity, hypothesizing that variances in bacterial strain cell wall compositions could account for this diversity [37]. Further insights emerge from the study of NiONPs produced from stevia leaf extract, which exhibited heightened efficacy against Gram-negative bacteria. Meanwhile, MnONPs derived from an Abutilon indicum leaf extract demonstrated formidable antibacterial effects encompassing both Gram-negative and Gram-positive bacteria. These findings underscore that the nature of the synthesized NPs exerts a discernible influence on antimicrobial potency. Additionally, the composition of phytochemicals coating their surfaces, an attribute shaped by the specific plant extract employed for NP synthesis, further contributes to the nuanced antimicrobial responses observed [38]. Various potential mechanisms underlie the antibacterial activity of nanoparticles (NPs), encompassing disruption of cell walls, disintegration of cell membranes, substantial generation of free radicals, targeted interactions with proteins, fragmentation of DNA, inhibition of vital enzymes, loss of cellular fluids, and perturbations in electron transport. Furthermore, bio-mediated NPs could trigger an antifungal response through excessive reactive oxygen species (ROS) production, albeit research in this context remains limited to fungi. Notably, investigations into the antifungal efficacy of these NPs remain relatively scarce. Despite notable advancements in our comprehension of the antimicrobial prowess exhibited by plant-based NPs, significant gaps persist in our understanding of their precise modes of action, potential toxicity, and ramifications for the environment [39].

1. **Agricultural Applications**

The antimicrobial efficacy detailed in the preceding section carries significant implications for safeguarding crops against agricultural pathogens. Notably, ZnONPs have emerged as valuable assets in agriculture, displaying anti-phytopathogenic properties against both bacteria and fungi. This has been exemplified by ZnONPs derived from lemon fruit effectively countering the soft rot bacteria pathogen Dickeya dadantii, and fungicidal ZnONPs synthesized using a Eucalyptus globules extract, targeting major pathogens impacting apple orchards. It's noteworthy that both ZnONPs and TiO2NPs, sourced from lemon fruit, demonstrated antibacterial activity against D. dadantii. Furthermore, AgNPs derived from wheat extracts showcased a significant role in alleviating the detriments of salinity stress on wheat crops. This effect was achieved by modulating abscisic acid concentrations, ion balance, and defense mechanisms encompassing both enzymatic and non-enzymatic antioxidants. Intriguingly, ZnONPs exhibited favorable attributes of low toxicity and the capability to enhance the antioxidant response of flax seedlings [40].

1. **DISCUSSION**

The discussion surrounding plant-based green synthesis of nanomaterials is a dynamic and multifaceted discourse that encompasses various scientific, technological, environmental, and societal dimensions. This emerging field has garnered significant attention due to its potential to revolutionize traditional nanomaterial synthesis methods and address various challenges in sectors ranging from healthcare to agriculture.

1. **Scientific Advancements:** Researchers have made significant strides in understanding the fundamental mechanisms underlying plant-based green synthesis. The utilization of plant extracts as natural sources of reducing and stabilizing agents showcases the ingenuity of this approach. The interaction between phytochemicals and metal ions during the synthesis process, leading to the formation of nanomaterials, has been a subject of thorough investigation. Additionally, the manipulation of parameters such as pH, temperature, and concentration has allowed scientists to fine-tune the properties of the resulting nanoparticles, tailoring them for specific applications.
2. **Environmental Sustainability:** One of the most compelling aspects of plant-based green synthesis is its inherent eco-friendliness. By utilizing natural extracts, this approach significantly reduces the need for toxic chemicals and energy-intensive processes that are typical of conventional nanoparticle synthesis. This aligns with the principles of green chemistry and sustainable manufacturing, contributing to a reduced ecological footprint.
3. **Biomedical Applications:** The potential of plant-based nanomaterials in the biomedical field is particularly promising. Their biocompatibility, reduced toxicity, and potential for targeted drug delivery have sparked interest in cancer therapy, drug delivery, and disease diagnostics. The development of nanovaccines and multifunctional nanomaterials capable of both treatment and imaging further underscores their versatility.
4. **Agricultural Impact:** In agriculture, these nanomaterials hold the potential to revolutionize crop protection and enhance agricultural yields. The antimicrobial properties of plant-based nanoparticles can combat pathogenic bacteria and fungi, contributing to sustainable farming practices and reducing the need for chemical pesticides.
5. **Challenges and Considerations:** However, challenges remain. The precise mechanisms of action of plant-based nanomaterials need further elucidation, and concerns about their potential toxicity require thorough investigation. Regulatory frameworks governing the production, safety assessment, and commercialization of these materials need to be developed to ensure responsible adoption.
6. **Interdisciplinary Collaboration:** The discussion also highlights the significance of interdisciplinary collaboration. Scientists, engineers, chemists, biologists, and medical professionals must collaborate to unlock the full potential of plant-based green synthesis. This convergence of expertise enriches the field, leading to innovative breakthroughs and holistic solutions.
7. **Ethical and Societal Implications: The** societal implications of plant-based nanomaterials are also part of the discourse. As these materials advance towards clinical applications and commercialization, ethical considerations regarding safety, informed consent, and equitable access need to be addressed. In conclusion, the discussion on plant-based green synthesis of nanomaterials encompasses a broad spectrum of scientific, technological, environmental, and societal dimensions. This innovative approach has the potential to reshape industries, promote sustainability, and drive advancements in fields ranging from medicine to agriculture. As researchers, policymakers, and stakeholders engage in this dialogue, the trajectory of this field will undoubtedly be influenced by their collective insights and actions [41].
8. **FUTURE ASPECTS**

Looking ahead, the future of plant-based green synthesis of nanomaterials is poised for exciting advancements and transformative impacts across various fields. As researchers delve deeper into this innovative approach, several key aspects are anticipated to shape its trajectory:

* 1. **Enhanced Understanding of Mechanisms:** Continued research will unravel the intricate mechanisms underlying the synthesis of nanomaterials using plant extracts. A deeper comprehension of how phytochemicals influence the formation and properties of nanoparticles will enable precise tailoring of nanomaterial characteristics for specific applications.
  2. **Multifunctional Nanomaterials:** Exploration of novel plant sources and extraction methods will likely lead to the creation of multifunctional nanomaterials with diverse properties. These materials could simultaneously possess therapeutic, diagnostic, and imaging capabilities, revolutionizing precision medicine and targeted therapies [42].
  3. **Integration of AI and Data Analytics:** The integration of artificial intelligence and data analytics will accelerate the identification of optimal plant candidates for specific nanomaterial synthesis, enabling efficient screening and customization of nanomaterial properties [43].
  4. **Eco-Friendly Production and Scale-up:** Developing scalable and sustainable methods for large-scale production of plant-based nanomaterials will be a key focus. Strategies to minimize resource consumption, waste generation, and energy usage will align with environmental conservation goals.
  5. **Clinical** **Translation:** As research progresses, clinical trials will play a pivotal role in validating the safety and efficacy of plant-based nanomaterials in human applications. This will pave the way for their integration into mainstream medical practices.
  6. **Agriculture and Environmental Remediation:** Plant-based nanomaterials hold immense potential in enhancing crop yields, combating agricultural pathogens, and contributing to sustainable farming practices. Furthermore, their utilization in environmental remediation, such as water purification and pollutant removal, could contribute to addressing pressing ecological challenges.
  7. **Regulation and Safety Standards:** The development of regulatory frameworks and safety standards specific to plant-based nanomaterials will be essential to ensure their responsible and ethical use across industries.
  8. **Interdisciplinary Collaboration:** Collaborations between researchers from diverse fields such as biology, chemistry, material science, and medicine will foster cross-pollination of ideas and drive innovation in plant-based nanomaterial synthesis.
  9. **Education and Outreach**: Raising awareness among the public about the potential benefits and risks of plant-based nanomaterials will be crucial for informed decision-making and responsible adoption. In essence, the future of plant-based green synthesis of nanomaterials holds immense promise for addressing complex challenges across medicine, agriculture, environment, and beyond. As technology and knowledge continue to evolve, these nanomaterials have the potential to reshape industries and contribute to sustainable and impactful solutions on a global scale [44].

1. **CONCLUSION**

In conclusion, the field of plant-based green synthesis of nanomaterials has yielded remarkable advancements and promising prospects across diverse applications. This environmentally conscious approach leverages the rich repertoire of phytochemicals present in various plants to create nanoparticles with distinct properties and functionalities. The utilization of plant extracts as reducing and stabilizing agents has enabled the production of nanomaterials with enhanced bioavailability, reduced toxicity, targeted delivery, and biodegradability. This methodology has been successfully applied to a range of nanomaterials, including metal and metal oxide nanoparticles, nanotubes, and nanovaccines, among others. These nanomaterials exhibit remarkable potential in combatting various challenges, from multidrug-resistant bacteria to cancer cells, showcasing their versatility in the realms of medicine, agriculture, and beyond. While significant progress has been made in understanding the antimicrobial and therapeutic capabilities of these nanomaterials, challenges remain. Detailed elucidation of the precise mechanisms of action, potential toxicity, and long-term environmental impact is crucial for their safe and effective integration into practical applications. Furthermore, efforts to standardize production methods and ensure reproducibility are essential for advancing this field. In essence, the plant-based green synthesis of nanomaterials represents a frontier where innovative strategies harmonize with ecological responsibility. As researchers continue to unravel the potential of these nanomaterials, it is evident that this approach holds immense promise for shaping a more sustainable and impactful future across diverse domains, ranging from medicine to agriculture and beyond.

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