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Review Article

Breaking Barriers in Eco-Friendly Synthesis of Plant-Mediated Metal/Metal Oxide/Bimetallic Nanoparticles: Antibacterial, Anticancer, Mechanism Elucidation, and Versatile Utilizations

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Nanotechnology has emerged as a promising field in pharmaceutical research, involving producing unique nanoscale materials with sizes up to 100 nm via physiochemical and biological approaches. Nowadays more emphasis has been given to eco-friendly techniques for developing nanomaterials to enhance their biological applications and minimize health and environmental risks. With the help of green nanotechnology, a wide range of green metal, metal oxide, and bimetallic nanoparticles with distinct chemical compositions, sizes, and morphologies have been manufactured which are safe, economical, and environment friendly. Due to their biocompatibility and vast potential in biomedical (antibacterial, anticancer, antiviral, analgesic, anticoagulant, biofilm inhibitory activity) and in other fields such as (nanofertilizers, fermentative, food, and bioethanol production, construction field), green metal nanoparticles have garnered significant interest worldwide. The metal precursors combined with natural extracts such as plants, algae, fungi, and bacteria to get potent novel metal, metal oxide, and bimetallic nanoparticles such as Ag, Au, Co, Cu, Fe, Zr, Zn, Ni, Pt, Mg, Ti, Pd, Cd, Bi_2O_3, CeO_2, Co_3O_4, $CoFe_2O_4$, CuO, Fe_2O_3, MgO, NiO, TiO_2, ZnO, ZrO_2, Ag-Au, Ag-Cr, Ag-Cu, Ag-Zn, Ag-CeO_2, Ag-CuO, Ag-SeO_2, Ag-TiO_2, Ag-ZnO, Cu-Ag, Cu-Mg, Cu-Ni, Pd-Pt, Pt-Ag, ZnO-CuO, ZnO-SeO, ZnO-Se, Se-Zr, and Co-Bi_2O_3. These plant-mediated green nanoparticles possess excellent antibacterial and anticancer activity when tested against several microorganisms and cancer cell lines. Plants contain essential phytoconstituents (polyphenols, flavonoids, terpenoids, glycosides, alkaloids, etc.) compared to other natural sources (bacteria, fungi, and algae) in higher concentration that play a vital role in the development of green metal, metal oxide, and bimetallic nanoparticles because these plant-phytoconstituents act as a reducing, stabilizing, and capping agent and helps in the development of green nanoparticles. After concluding all these findings, this review has been designed for the first time in such a way that it imparts satisfactory knowledge about the antibacterial and anticancer activity of plant-mediated green metal, metal oxide, and bimetallic nanoparticles together, along with antibacterial and anticancer mechanisms. Additionally, it provides information about characterization techniques (UV–vis, FT-IR, DLS, XRD, SEM, TEM, BET, AFM) employed for plant-mediated nanoparticles, biomedical applications, and their role in other industries. Hence, this review provides information about the antibacterial and anticancer activity of various types of plant-mediated green metal, metal oxide, and bimetallic nanoparticles and their versatile application in diverse fields which is not covered in other pieces of literature.

1. Introduction

In the 21st century, the most demanded and new promising technology for research purposes is nanotechnology, where novel synthetic techniques have been used for the synthesis of nanomaterials, for example, MNPs, MONPs, BMNPs, carbon nanotubes, quantum dots, graphene composite, etc. [1–3]. The word "nano" in NPs means small, due to this surface area is very specific which gives potential effect and high intrinsic properties such as surface reactivity [4]. These properties are responsible for their portability and safe and easy bodily administration [5, 6]. Nanotechnology through

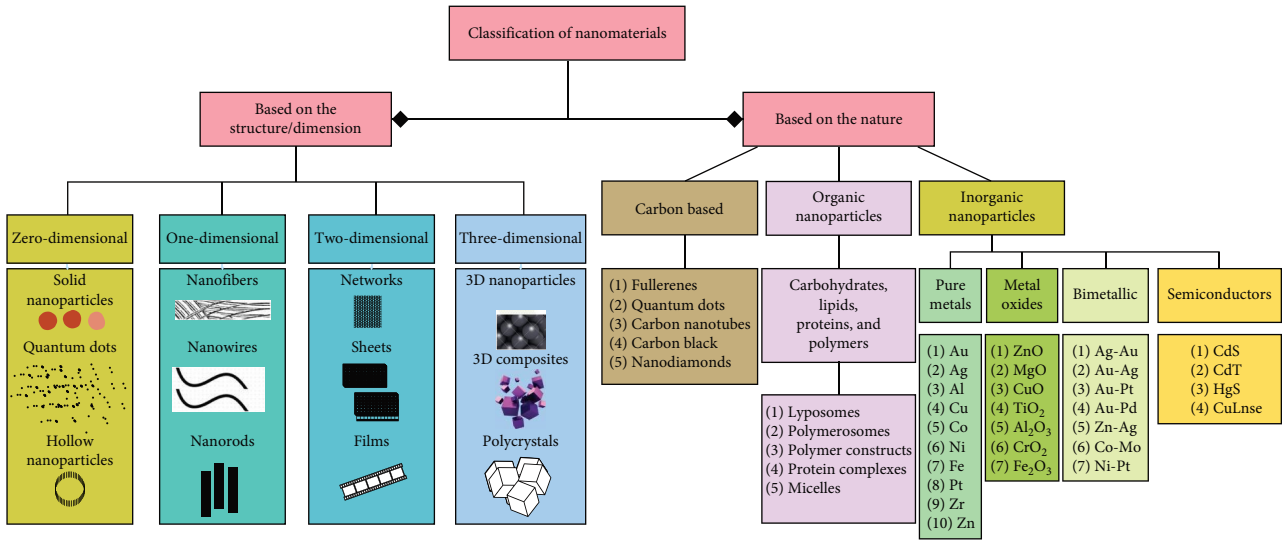

Figure 1: Classification of nanomaterials.

the formation of nanomaterials of varying sizes starting from 1 to 100 nm has proven itself in almost all fields like medicine, nutrition, energy, agriculture, engineering, physics, material science, computer science, organic chemistry, and inorganic chemistry [7]. Nanomaterials are broadly classified based on the structure and nature of the nanomaterials (Figure 1). Based on structure, it is divided into four subcategories such as zero-dimensional, one-dimensional, two-dimensional, and three-dimensional nanomaterials. On the other hand, it is subdivided into three parts based on nature including carbon-based nanomaterials (fullerenes, quantum dots), organic (liposomes), and inorganic nanomaterials (Ag, Au, ZnO, CuO, Ag-Au, etc.). Among these, inorganic/metal nanoparticles have recently received attention due to their remarkable features, strong qualities, unique biological applications (antibacterial and anticancer), least cost upon synthesis, and becoming environment-friendly when produced by green synthetic routes other than physical and chemical routes [8, 9]. Green synthesis is an ecofriendly and cost-effective synthetic route where metal precursors are combined with required natural sources, such as plant extracts, microorganisms, bacteria, yeast to produce suitable NPs [10].

In recent years, frequent utilization of various NPs become enhanced by the economic sector but the major concern is about the environmental and biological safety of preparations. While avoiding any related toxicity, green nanotechnology offers tools for converting biological systems to environmentally friendly methods of synthesizing nanomaterials [11, 12]. In green nanotechnology methods, natural sources are utilized other than hazardous chemicals utilized by physicochemical methods for NPs synthesis. Green nanotechnology can create secure, environmentally beneficial NPs without using hazardous chemicals by combining the principles of green chemistry [13, 14]. The synthesis of green NPs is a novel field of nanotechnology that increases day by day and become more frequent due to its vast therapeutic applications (antibacterial, anticancer, antiviral, analgesic, anticoagulant, biofilm inhibitory activity) in the pharmaceutical industry both in vivo and in vitro [15–18]. The benefits of noble NPs, which are crucial for medical applications, include great biocompatibility, stability, and the potential for large-scale synthesis without the use of organic solvents, which have a favorable impact on biological systems.

In the modern period, a variety of health issues are faced by common people, the most serious of which is treatment resistance in microbes and cancer cells. Bacterial contamination produces several health issues in all individuals, including illness, death, and organ deformities, all of which can be treated with medicines [19]. The widespread use of antibiotics is seen in the numerous abnormalities and full suppression of bacterial domains. Antibiotics also damage good microorganisms, and their long-term usage suppresses the nerve action system. As a result, researchers are working on developing creative strategies to limit dangerous evolution and dispersion. Nanoscale materials are always a novel and effective antibacterial output for the scientific community. Biogenic nanoparticles improve bacterial resistance in a variety of bacterial strains [20]. On the other hand, cancer is a disease caused by the evasion of one's own protective system against malignant cells and has caused widespread illness and mortality during the last few decades. Radiotherapy, chemotherapy, and immunotherapy are typical cancer treatments, but, like a double-edged sword, these techniques may have plenty of adverse effects while preventing the growth of cancer. For example, the systemic cytotoxicity and severe side effects of radiotherapy are the most significant barriers to their optimum therapeutic efficacy for cancer [21]. Furthermore, chemotherapy medicines, which always exhibit poor selectivity, can readily kill a large number of normal cells, weaken the immune system, and lead to treatment resistance. Although immunotherapy is gaining popularity around the world, it is still exceedingly expensive and can be fatal if anticancer immune responses are not effectively managed. Based on the existing state of cancer treatment tactics, there is an urgent need to develop new cancer-fighting technology. Plant-mediated NPs are a fascinating area in the

search for novel anticancer treatments. These NPs, which can utilize nature's power, are generated from plant extracts and have amazing anticancer potential. Plant's bioactive components such as flavonoids, polyphenols, and alkaloids play a vital role in the synthesis of nanoparticles [22]. These plant-mediated NPs not only inherit the inherent anticancer properties of the plant phytoconstituents but also offer unique advantages in terms of biocompatibility and reduced toxicity. The broad phytochemical variability contributes to varied anticancer effects, affecting multiple stages of cancer development. Targeted drug delivery is increased by surface alterations regulated by plant phytoconstituents, ensuring a targeted impact on cancer cells while sparing healthy tissues. Furthermore, the antioxidant qualities of many plant-derived compounds protect against oxidative stress, which is a hallmark of cancer growth [23]. The synergy between the inherent bioactivity of plants and the tailored properties of synthetic NPs results in a potent combination, capable of addressing the complexities of cancer biology. Thus, plant-mediated NPs synthesis emerges as a promising candidate, combining the wisdom of traditional herbal medicines with cutting-edge nanotechnology to establish a new paradigm in cancer treatment. Hence, researchers have shown keen interest in development of biologically synthesized green NPs (MNPs, MONPs, BMNPs) which are hazardous to cancer cells but not harmful to normal cells [24]. Due to their selective nature various metal precursors combined with different parts of plant extracts which contains essential phytoconstituents (vitamins, proteins, enzymes, flavonoids, phenolic compounds, alkaloids, glycosides, tannins, etc.) that act as a reducing, capping and stabilizing agent. This ultimately leads to the formation of suitable ecofriendly green MNPs, MONPs, and BMNPs that are responsible for antibacterial and anticancer effects [25]. The metals, metal oxides that are used by the researchers for the development of MNPs, MONPs, and BMNPs are Ag, Au, Co, Cu, Fe, Zr, Zn, Ni, Pt, Mg, Ti, Pd, Cd, Bi_2O_3, CeO_2, Co_3O_4, $CoFe_2O_4$, CuO, Fe_2O_3, MgO, NiO, TiO_2, ZnO, and ZrO_2, respectively [26–30]. Plant-mediated MNPs, MONPs, and BMNPs have gained popularity in recent years due to their unique physical features such as quantum effect, high surface area, mobility, chemical, mechanical, thermal, optical, catalytic, and magnetic capabilities. Both mono and BMNPs have applications in a variety of disciplines, including antibacterial, anticancer, antiviral, analgesic, anticoagulant, biofilm inhibitory activity, nanofertilizers, fermentative, food and bioethanol production, and construction field. Furthermore, the antibacterial and anticancer activity of plant-mediated MNPs, MONPs, and BMNPs have been intensively researched for past few years. On the basis of all findings, this present review gives information about the antibacterial and anticancer activity of plant-mediated green MNPs, MONPs, and BMNPs and their mechanisms. It also focused on unique characterization techniques employed for plant-mediated green NPs (MNPs, MONPs, and BMNPs) along with versatile applications in medical field and in other fields.

2. Synthetic Approach of NPs

The synthesis of NPs interestingly increases day by day due to their larger therapeutic benefits with lesser side effects. As per the literature, the two basic fundamental approaches

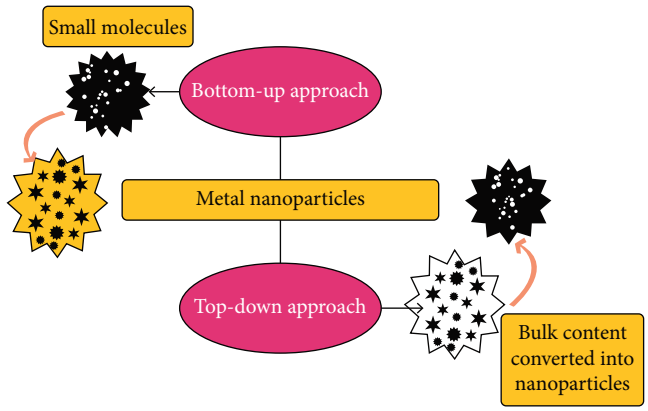

Figure 2: Diagrammatic representation of synthetic approaches for NPs.

have been proposed for the synthesis of NPs of desired functionalities, size, and shape, i.e., top-down and bottom-up approaches, as shown in Figure 2 [31]. The top-down and bottom-up approach includes various methods to synthesize NPs such as (i) chemical methods, (ii) physical methods, and (iii) biological methods, as shown in Figure 3, whereas top-down methods include different types of lithographic techniques such as sputtering (kinetic), ball milling, etching (chemical), electroexplosion (chemical), and laser ablation (thermal) [32, 33]. In the top-down method, bulk materials are converted into smaller size NPs through mechanical abrasion, whereas, in the bottom-up method, small atoms or molecules are combined to form a new entity via chemical forces. Bottom-up methods include vapor deposition, aerosol process, chemical deposition, laser pyrolysis, sol–gel process, plasma spraying synthesis, and green synthesis [34]. Top-down method includes physical methods, whereas chemical and biological methods are a part of bottom-up methods.

2.1. Physical Synthesis Methods. Physical methods involve the manipulation of physical properties to produce NPs. These methods include methods like laser ablation, evaporation–condensation, and ball milling. In laser ablation, a high-energy laser is focused on a target material, causing its vaporization and subsequent NPs formation. Similarly, evaporation–condensation involves vaporizing a precursor material, which then condenses into NPs. Ball milling crushes and grinds bulk materials into nanoscale particles [35]. Physical methods often yield highly pure NPs with precise control over size and shape. However, they may require expensive equipment, and high energy input, and can be limited in their scalability [36].

2.2. Chemical Synthesis Methods. Chemical methods involve the reduction of metal salts or chemical precursors to form NPs. Common approaches include chemical precipitation, sol–gel synthesis, and hydrothermal synthesis. In chemical precipitation, reactants are mixed to form NPs through a chemical reaction. Sol-gel synthesis involves the formation of a colloidal suspension, which then solidifies into NPs. Hydrothermal synthesis uses high-temperature and pressure conditions to produce NPs. These methods are versatile and scalable, allowing for the synthesis of a wide range of NPs

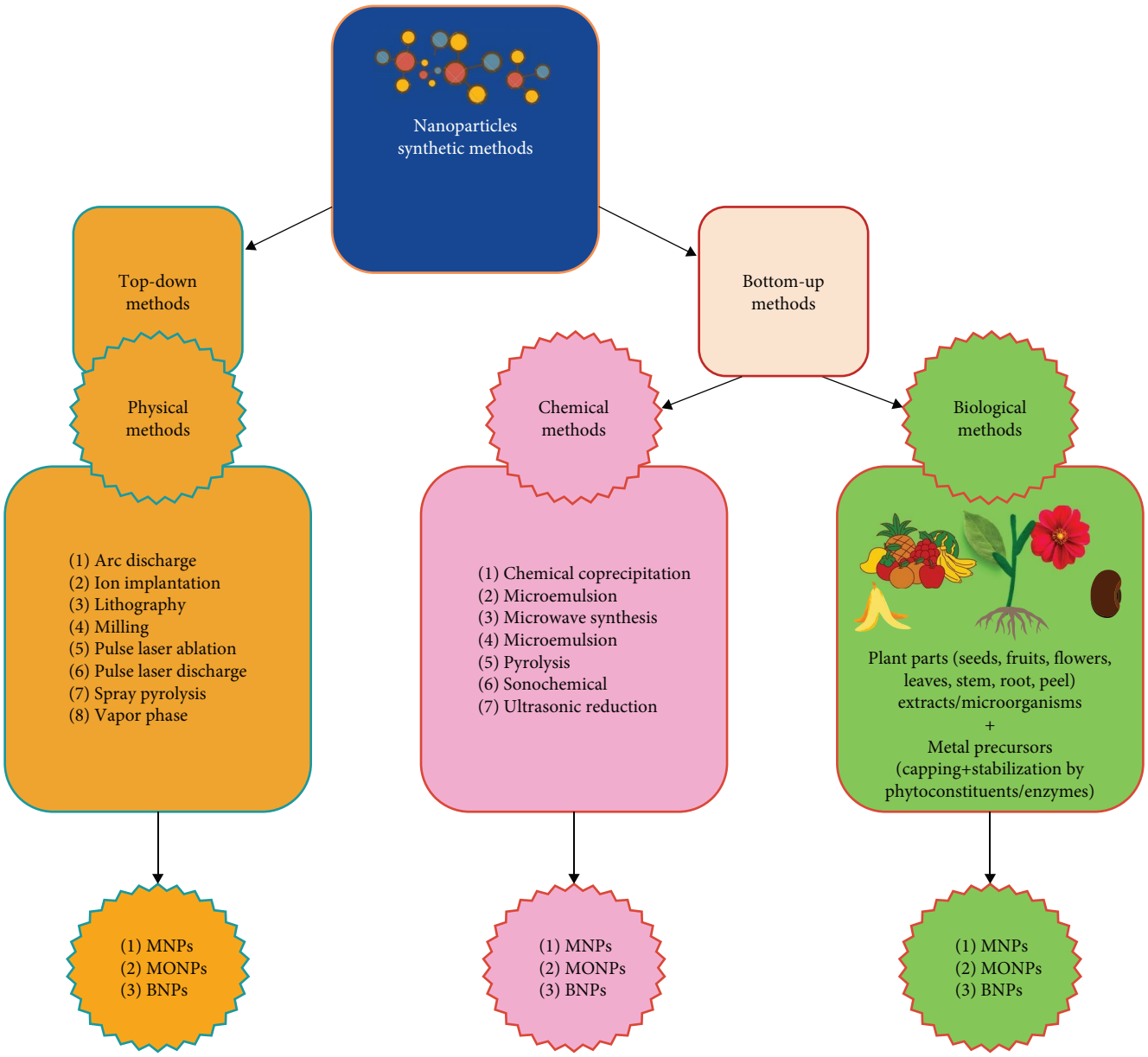

Figure 3: Physiochemical and biological methods of synthesis of nanoparticles.

with control over size, shape, and composition. However, they often require the use of hazardous chemicals and generate toxic byproducts [36, 37]

2.3. Biological Synthesis Methods. Biological methods, also known as green synthesis, utilize plants, living organisms like bacteria, fungi, and algae to synthesize NPs. These organisms naturally secrete enzymes or metabolites that reduce metal ions into NPs. Biological synthesis is considered environmentally friendly as it eliminates the need for toxic chemicals and high-energy inputs [38, 39]. Moreover, it often yields NPs with narrow size distributions and surface functionalization, making them suitable for various applications. The scalability of biological synthesis depends on the growth of the biological organism, which can sometimes be slower than chemical methods. However, it offers a sustainable and low-cost alternative for NPs production of different shapes spherical, ellipsoidal, cubical, triangular, pentagonal, and rod-shaped [40–42].

2.4. Superiorities of Biological Synthesis. However, chemically and physically synthesized NPs suffer from various challenges such as environmental stability, expensive procedures, skilled operators required, issues created during the assembling of devices, could not be reused again, and may cause toxicity. Interestingly, the physical and chemical methods are used most frequently for the synthesis of NPs but the major drawback of these techniques is their high cost and utilization of highly toxic chemicals which are hazardous to nature and living health [43]. The biological synthesis of NPs offers several advantages over traditional physical and chemical methods [44]. First, it is environmentally benign, reducing

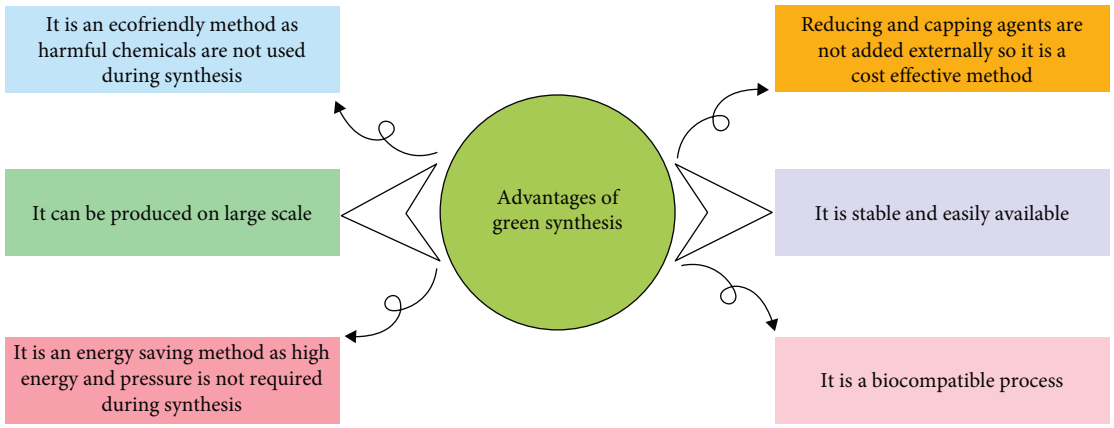

Figure 4: Highlights the multiple advantages of green synthesis.

the use of hazardous chemicals and minimizing waste generation. This makes it a sustainable and eco-friendly option. Second, biological synthesis often results in NPs with superior biocompatibility, which is crucial for biomedical applications. Additionally, the ability to engineer the biological system allows for the production of NPs with tailored properties, such as size, shape, and surface functionalization. Furthermore, biological synthesis is cost-effective, utilizing renewable resources like plant extracts or microorganisms. Overall, the biological synthesis of NPs aligns with green chemistry principles, making it an attractive choice for various industrial and medical applications, particularly in contexts where sustainability and biocompatibility are essential [45]. So, it is essential to go for green nanotechnology to overcome these challenges and develop novel NPs of the desired size and shape along with excellent therapeutic efficacy. Hence, nowadays researchers more focusing on green synthesis techniques to produce desirable NPs that remove toxicity and reduce pollution.

3. Advantages of One-Step Green Synthesis

Green synthesis is a type of bottom-up approach, where natural components such as plant extracts, fungi, yeast, bacteria, and algae are used to synthesize sable and eco-friendly NPs [46]. For large-scale production of biogenic NPs, plant extracts are widely used instead of microorganisms such as fungi and bacteria. This technique avoids many disadvantages that were found in other techniques, in this technique, synthesis of NPs is obtained at a low cost and requires mild pH, temperature, and pressure [47]. Overall green mediated approach for the synthesis of NPs is a route where researchers can synthesize stable NPs. In this approach, there is no need to add stabilizing and capping agents as required by some other chemical and physical methods because plant biomolecules (amino-acids, carbohydrates, proteins, flavonoids, phenolic acids, tannins, terpenoids, glycosides, alkaloids, etc.) themselves work as excellent capping and stabilizing agents during the synthesis of NPs [48]. Plant-mediated NPs synthesis is a "one-step" easy procedure where the plant extracts are employed with metal salt and synthesis is completed within a few minutes or hours at room temperature. Generally, three steps were followed during green synthesis: selective solvent medium, an eco-friendly reducing agent or stabilizing agent, and a suitable nontoxic component as a capping agent which must be used to stabilize the synthesized NPs [49]. A few advantages of green synthesis are illustrated in Figure 4 [50]. Researchers pay more attention to this technique and synthesize various MNPs, MONPs, and BNPs by utilizing different types of metal precursors such as Au, Ag, Cu, Zn, Fe, Pt, Ni, Co, Mg, Ti, Pd, Cd, Zr, ZnO_2, CuO, TiO_2, NiO, Bi_2O_3, CeO_2, Fe_2O_3, Au-Ag, Au-Pd, Ag-Au, Ag-Cu, Cu-Ag, Fe-Cu, Fe-Pd, Ti-Ni, respectively, that shows potential anticancer and antimicrobial activity [51].

4. Methods to Develop Green NPs

To develop NPs of perfect shape, size, and functionalities, two unique methods have been investigated, first is the top-down and another is bottom-up method [52]. The basic difference between these two methods is their starting component for example in the top-down method bulk material is the starting component which is broken down into small particles by applying some external force via various methods like chemical, thermal, mechanical, physical, sputtering, laser ablation, etc., and in bottom-up method, starting material is an atom which turns into a smaller nucleus which further grows into a small size NPs. In the top-down method, different types of mills can be used such as ball mill, laser ablation, ion sputtering, and abrasion methods to prepare semicrystalline structures and nanocomposites. The bottom-up method includes the solid-state method, liquid state, gas phase, biological methods, and some other methods such as sono-decomposition, electrochemical methods, chemical reduction, sol–gel methods, and spray pyrolysis [4]. In the abovementioned methods, a top-down method is costlier during implementation, it is hard to obtain fine edges and surfaces in synthesized NPs due to roughness and cavities, whereas, in the bottom-up approach, excellent NPs were obtained as per literature. Along with this, there is no need to remove any waste material and easily obtain small-size NPs due to the great control of size during the formation of NPs [53]. Development methods for the NPs can be natural and synthetic, both having different origins with unique properties. Many common techniques that are used for the

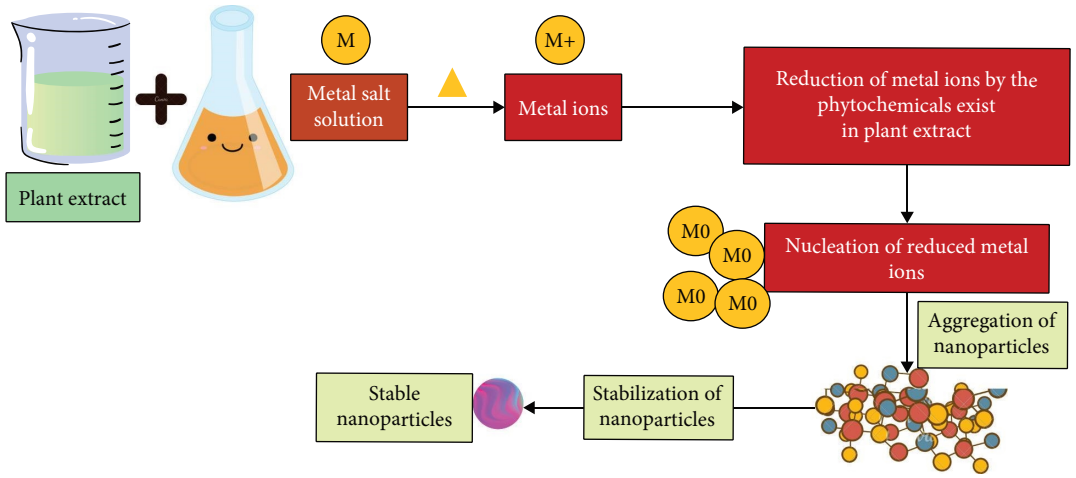

Figure 5: Basic representation of the plant-mediated NPs development method.

synthesis of NPs come with several disadvantages' high operation cost, energy insufficiency, toxicity, and environmental damage. These techniques often require several steps such as highly expensive instruments, toxic chemicals, and controlled environments like controlled pressure, pH, and temperature. On the other hand, these methods often generate many byproducts which are toxic to our environment. Overall, we can say many physical and chemical process used for the synthesis of NPs produces harmful chemicals that are highly toxic and costly is one of the reasons for biological hazards. Therefore, it is essential to generate an eco-friendly approach which is highly recommended by many researchers [54]. Nowadays scientists more focusing on the green synthesis of NPs. Green synthesis is a part of the bottom-up approach in which natural components are used as a starting material such as plant extracts, bacteria, yeast, and algae [32]. This technique avoids many disadvantages that were found in other techniques, here the synthesis of NPs was obtained at a low cost and required mild pH, temperature, and pressure [55]. Overall green mediated approach for the synthesis of NPs is a route where we can synthesize stable NPs. Here there is no need to add stabilizing and capping agents as required by some other chemical and physical methods because plant components themselves work as excellent capping and stabilizing agents during the synthesis of several types of NPs [56].

Plant-mediated NPs synthesis is an easy procedure where the plant extracts are employed with metal salt and synthesis is completed within a few minutes or hours at room temperature, as shown in Figure 5 [57]. Generally, three steps were followed during green synthesis—selective solvent medium, an eco-friendly reducing agent or stabilizing agent, and a suitable nontoxic component as a capping agent which must be used to stabilize the synthesized MNPs. Researchers pay more attention to this technique and synthesize various NPs by utilizing Au, Ag, Cu, Zn, Fe, ZnO, CuO, TiO_2, etc., which shows the potential therapeutic effects [58]. The metal salt solution is combined with plant extract under varied reaction conditions for the creation of NPs via plant extract or microorganism extract. The overall pace of formation of NPs, their stability, and yield are fully dependent on parameters such as metal salt concentration, phytochemicals content in the extracted portion [59], kind of phytoconstituents, reaction pH, and temperature, particle size, and surface change. Because phytochemicals included in the plant extracts can easily reduce metal ions, they are regarded as a suitable source for the synthesis of NPs, acting as both a stabilizing and reducing agent [60, 61]. Various phytochemicals found in plants, including sugars (carbohydrates), proteins (amino acids), terpenoids, aldehydes, ketones, carboxylic acids, and flavonoids, may result in the reduction of metal ions during the creation of NPs.

Additionally, oxygen is created and connected to the metal ions in their reduced state that were either taken from the atmosphere or phytochemicals that had been broken down. The creation of NPs is aided by the electrostatic attraction that links metal oxide ions to one other. Additionally, phytochemicals stabilize the synthetic product by reducing particle aggregation [62]. In plant extract, functional amino acid and protein groups play a crucial role as reducing agent that aids in the reduction of metallic ions [63].

5. Factors Affecting NPs Synthesis

The synthesis of green NPs, often referred to as green synthesis, involves the reduction of metal ions to form NPs using environmentally friendly and sustainable methods. Several factors can influence the synthesis of green NPs such as choice of plant extract or biomaterial: green synthesis relies on the use of plant extracts, microbial cultures, or other biologically derived materials as reducing and stabilizing agents. The choice of the plant or biomaterial can significantly affect the synthesis process, as different sources may have varying concentrations of reducing agents and phytochemicals. Various reaction parameters can influence the synthesis of NPs, including temperature, pH, and reaction time. These conditions can affect the rate of reduction and nucleation, ultimately determining the size and shape of the NPs [64, 65].

5.1. Plant Extraction Method. The method used to extract phytochemicals or biomolecules from plants can impact the

synthesis. Extraction methods, such as maceration, Soxhlet extraction, ultrasound-assisted extraction, and microwave-assisted extraction, can affect the yield and composition of the extract, which, in turn, influences NPs synthesis [66].

5.2. Metal Precursor. The type and concentration of the metal precursor (such as, metal salts like silver nitrate, gold chloride, zinc nitrate, and copper sulfate) used in the synthesis play a crucial role in the development of desirable green NPs. Different metals have distinct properties and may require specific conditions for successful NPs formation [67].

5.3. Concentration of Biomaterial. The concentration of the plant extract or biomaterial used as a reducing agent can affect the synthesis process. Higher concentrations of reducing agents may result in a more rapid reduction of metal ions, potentially leading to smaller NPs [68].

5.4. Stirring and Agitation. Agitation, such as stirring or shaking, can influence the distribution of reactants and affect the rate of NPs formation. Proper mixing can help ensure uniform particle size and shape [68].

5.5. pH of the Reaction Medium. The pH of the reaction medium is critical, as it can influence the stability of NPs and the reduction kinetics. Different plant extracts have varying pH levels, and adjusting the pH may be necessary for optimal synthesis [69].

5.6. Temperature. Temperature can influence the reaction kinetics and the size of the NPs. Higher temperatures often result in faster reduction rates but may also lead to agglomeration or unwanted side reactions [70]. Incubation time is another factor which enhances the NPs size. The length of incubation time the reaction is allowed to proceed can typically lead to larger NPs.

5.7. Capping and Stabilizing Agents. During NPs synthesis methods, the use of capping or stabilizing agents, such as surfactants or proteins, to prevent NPs agglomeration and improve the stability of NPs but in the case of plant-based (green) synthetic approach, plants phytoconstituents itself plays a vital role as a capping, stabilizing, and reducing agents and helps in the synthesis of suitable NPs [71, 72]. Plant phytochemicals such as alkaloids, phenols, terpenes, saponins, alcohols, and proteins act as reducing and capping agents. Isolated phytochemicals aid in the repeatability of size and shape-controlled nanomaterials. These NPs are bioactive and have numerous biological and pharmacological applications [73].

5.8. Characteristics of the Plant Extract and Analysis. The phytochemical composition of the plant extract can vary based on factors like plant species, growth conditions, and harvest time. Different phytochemicals may have varied reducing capabilities, which affect the synthesis. The choice of characterization techniques, such as UV–visible spectroscopy, transmission electron microscopy (TEM), and X-ray diffraction (XRD) analysis, can impact the accuracy of size, shape, and composition analysis [74, 75].

5.9. Scaling-Up. The ability to scale up green synthesis methods from laboratory-scale to industrial-scale production can be challenging. Factors like reaction vessel size, agitation methods, and temperature control become even more critical during scale-up. Green synthesis offers a sustainable and eco-friendly approach to NPs production, and researchers often need to optimize these factors to achieve the desired NPs characteristics for specific applications, such as nanomedicine, catalysis, and sensing [76].

6. Factors Influencing the Biological Activity of Green Inorganic NPs

The biological activity of NPs is a subject of considerable interest and research in the fields of nanotechnology and biomedicine. NPs have gained attention due to their unique properties, such as tunable magnetic behavior, high surface area, and the ability to carry and deliver drugs or biomolecules to specific targets within the body. Several factors influence the biological activity of these NPs, and understanding them is crucial for their successful application in various biomedical applications.

6.1. Size and Surface Area. One of the most critical factors influencing the biological activity of inorganic NPs is their size and surface area. NPs with smaller sizes typically exhibit greater surface area-to-volume ratios, which enhance their interactions with biological molecules, cells, and tissues. This increased surface area allows for improved drug loading, cellular uptake, and targeting specificity, making smaller MNPs more effective in biomedical applications [77, 78].

6.2. Magnetic Properties. The magnetic properties of inorganic NPs, including their magnetization, coercivity, and remanence, can influence their biological activity. Magnetic NPs can be manipulated using external magnetic fields to enhance their targeting and retention at specific sites within the body, making them valuable tools for drug delivery and imaging applications [79, 80].

6.3. Surface Charge and Zeta Potential. The surface charge of inorganic NPs, characterized by their zeta potential, affects their stability, colloidal behavior, and interactions with biological molecules. NPs with appropriate surface charges can improve their dispersion in biological fluids, prevent aggregation, and enhance cellular uptake [81].

6.4. Surface Coating and Functionalization. The surface of inorganic NPs can be functionalized with various molecules, such as polymers, antibodies, or peptides, to modify their biological activity. Surface coatings can improve the stability of NPs in physiological environments, reduce toxicity, and enable specific targeting of cells or tissues. Functionalization also plays a crucial role in controlling drug release kinetics from NPs [82].

6.5. Composition and Concentration. The material composition of NPs is a critical factor. Different inorganic materials, such as metals (e.g., Au, Ag, Cu, Zn, Fe), metal oxides (e.g., ZnO, CuO, TiO_2), and bimetallic (e.g., Ag-Au, Ag-Pd), can

have varying degrees of biocompatibility and toxicity. The concentration and dose of NPs administered to biological systems can influence their biological effects. Higher concentrations may lead to increased toxicity, while lower doses may have more targeted therapeutic effects [83].

6.6. Agglomeration. The tendency of NPs to agglomerate or disperse in biological fluids can impact their biological activity. Agglomeration may lead to reduced cellular uptake and altered toxicity profiles, while well-dispersed NPs may have better bioavailability. Proper surface functionalization and stabilization are essential to prevent unwanted particle aggregation, ensuring that NPs maintain their desired properties and functionalities in physiological conditions [84].

6.7. Biocompatibility and Toxicity. Biocompatibility is a crucial factor in determining the biological activity of NPs. The composition, surface chemistry, and size of NPs can influence their cytotoxicity and potential adverse effects on cells and tissues. Biocompatible NPs are less likely to induce inflammation, cell death, or other adverse reactions, making them safer for use in biomedical applications [85]. The specific biological environment in which NPs are introduced, including factors like pH, temperature, and the presence of other biomolecules, can affect their behavior and biological activity.

6.8. Biological Response and Exposure Time. The biological response to NPs can vary among individuals and may be influenced by factors such as genetics, immune system status, and overall health. The duration of exposure to NPs can influence their biological effects. The biological activity of NPs is influenced by a complex interplay of factors, including size, surface properties, magnetic behavior, biocompatibility, and functionalization. Researchers continue to explore and optimize these factors to harness the full potential of NPs in various biomedical applications, such as drug delivery, imaging, and targeted therapy [86]. Understanding how these factors affect NPs behavior in biological systems is essential for developing safe and effective NPs for use in healthcare and medicine, paving the way for innovative and personalized treatments in the future.

7. Antibacterial and Anticancer Action of Green NPs (MNPs, MONPs, BMNPs)

Plant-mediated green NPs such as MNPs, MONPs, and BMNPs are widely used in many industries like pharmaceutical, agriculture, chemical industries, and electrical. Various types of green NPs (Ag, Au, Co, Cu, Fe, Zr, Zn, Ni, Pt, Mg, Ti, Pd, Cd, Bi_2O_3, CeO_2, Co_3O_4, $CoFe_2O_4$, CuO, Fe_2O_3, MgO, NiO, TiO_2, ZnO, ZrO_2, Ag-Au, Ag-Cr, Ag-Cu, Ag-Zn, Ag-CeO_2, Ag-CuO, Ag-SeO_2, Ag-TiO_2, Ag-ZnO, Cu-Ag, Cu-Mg, Cu-Ni, Pd-Pt, Pt-Ag, ZnO-CuO, ZnO-SeO, ZnO-Se, Se-Zr, Co-Bi_2O_3) were produce by combining metal precursors with plant extracts in a particular ratio to achieve maximum potential as antibacterial and anticancer agents [87]. These metals are combined with numerous plants extract to get potent effects without side effects. For many years, scientists have shown keen interest in the development of MNPs, MONPs, and BMNPs by utilizing plant extracts and showed excellent antibacterial and anticancer action against tested pathogens and several types of cancers respectively.

7.1. Antibacterial and Anticancer Action of Green MNPs. According to the reports several metals such as Ag, Au, Co, Cu, Fe, Zr, and Ti are widely used for the production of MNPs by utilizing plant extracts that have shown potent benefits to human health [76]. Among them, Ag, Au, Co, Cu, Fe, Ni, and Zr NPs were reported for potent antimicrobial, antifungal, anticancer, antioxidant, anti-inflammatory, antidiabetic [88] larvicidal, and, antipythium activity, as shown in Table 1.

7.1.1. Ag NPs. Ag is a fascinating metal with many uses, it is cheaper than Au. For many years, Ag has been extensively used in nanobiotechnology to synthesize Ag NPs due to their greater stability and less chemical reactivity. Ag NPs have shown a significant role as an excellent antiviral, antibacterial, antifungal, anticancer, analgesic, bone cement, bone healing, wound healing, and dental treatment [110, 111]. In recent studies, several researchers have focused on the production of green Ag NPs by utilizing many natural biomolecules present in various plants such as proteins, amino acids, enzymes, alkaloids, polysaccharides, vitamins, and alcoholic compounds and showed a potent role in biomedicine, agriculture, wastewater treatment, mosquito control, food packaging, and safety [112]. The biosynthesis of Ag NPs has been placed by various biological sources like bacteria, fungi, yeast, actinomycetes, viruses, algae, and plant extract. All plant-mediated synthesized NPs are safe, simple, and easy to handle, as compared to other biological sources. As plants extracts consist of various biomolecules such as flavonoids, sterols, ascorbic acid, terpenoids, saponins, and b-phenylethylamines. These natural phytochemicals which are present in plant extracts act as stabilizing and reducing agents during the formation of Ag NPs [113]. Researchers have explored the therapeutic potential of Ag NPs as effective antibacterial agents against various human pathogens. The size of synthesized Ag NPs is small and the surface area is large so they can easily penetrate the cell wall of bacteria, destroy the cell membrane by producing reactive oxygen molecules, and interfere with the replication of DNA and protein synthesis, this may lead to cell death [114]. It was evaluated and reported that green synthesized Ag NPs are an important constituent for pest control and enhance crop yield so they can be widely used as biopesticides due to their antimicrobial action [115]. Numerous kinds of literature reported the novel use of NPs for the treatment of different kinds of cancers [116]. In the body, Ag NPs accumulate and interact with cancerous tissues such as stomatal cells, due to this numerous signaling pathways get activated and cause dysfunction of mitochondria, autophagy, oxidative stress, and endoplasmic reticulum stress resulting in cell death [117]. Several biomedical applications of Ag NPs have been reported in many articles such as antifouling, antioxidant, antiangiogenic, antiproliferative, antiquorum sensing, and anti-inflammatory. Ag NPs have been synthesized and evaluated as a

Table 1: Biological activity of green synthesized MNPs.

Synthesized NPs	Plant/method used	Tested pathogens/cancer cells	Biological application	References
Ag NPs	*Photinia glabra* fruit extract	*E. coli*, *S. aureus*, and Eca-109 cancer cells	Antibacterial, anticancer activity	[89]
Ag NPs	*Teucrium polium* extract	MCF-7 and MCF-10A cancer cell lines	Anticancer, antioxidant activity	[90]
Ag NPs	*Jacobaea maritima* aqueous leaf extract	*E. coli* and MCF-7 (breast cancer), A549 (lung cancer) cells	Antimicrobial activity	[91]
Ag NPs	*Lippia citriodora* aqueous leaf extract	*E. coli*, *S. typhi*, *B. subtilis*, and *S. aureus*	Antimicrobial, larvicidal, photocatalytic activity	[92]
Ag NPs	*Conocarpus lancifolius* fruits extract	*S. pneumonia*, *S. aureus*, *R. stolonifera*, *A. flavus*, and MDA MB-231 cells	Antimicrobial, anticancer activity	[93]
Ag NPs	Aqueous *Citrus limon zest* extract	*S. aureus* and *C. albicans*	Antibacterial, antioxidant activity	[94]
Ag NPs	*Alhagi graecorum* leaf extract	*C. albicans*, *C. glabrata*, *C. parapsilosis*, *C. tropicales*, and *C. krusei*	Antifungal, antitumor activity	[95]
Ag NPs	*Brachychiton populneus* leaf extract	U87 and HEK293 cell lines	Cytotoxic, antioxidant activity	[96]
Ag NPs	*Cymbopogon citratus* leaf extract	*S. paratyphi*, *S. flexneri*, *V. cholerae*, *B. cereus*, and *E. coli*	Antimicrobial activity	[97]
Ag NPs	*Euporbia serpens kunth* aqueous extract	*E. coli*, *S. typhi*, *C. albicans*, *A. alternata*, *F. gramium*, and *Artemia salina* (animal model)	Antimicrobial, antioxidative, insecticidal, and cytotoxic activity	[98]
Au NPs	*Gracilaria crassa* aqueous extract	*A. stephensi* larvae	Cytotoxicity activity	[99]
Au NPs	*Jatropha* integerrima flower extract	*B. subtilis*, *S. aureus*, *E. coli*, and *K. pneumoniae*	Antibacterial activity	[100]
Au NPs	*Physalis minima* aqueous extract	*S. aureus*, *P. aeruginosa*, *S. pneumoniae*, and *E. coli*	Antioxidant, antidiabetic, and antibacterial activity	[101]
Au NPs	*Verbascum thapsus* and *R. communis* ethanolic extracts	HT29 and SW480 colorectal cancer cells	Antiproliferative activity	[102]
Au NPs	Hibiscus and curcumin extract	HCT-116 and MCF-7 cells	Anticancer activity	[103]
Ag NPs and Au NPs	Aqueous extracts of root, stem, and leaf of *Capsicum chinense*	*S. aureus*, *E. coli*, *S. marcescens*, and *E. faecalis*	Antioxidant, antimicrobial activity	[104]
Co NPs	Orange peel aqueous extract	*E. coli*, *S. aureus*, *B. subtilis*, *K. pneumoniae*, and *A. niger*	Antioxidant, antimicrobial activity	[105]
Ni NPs	*Bacillus sphaericus* culture	*A. Subpictus*, *C. quinquefasciatus*, and *B. annulatus*	Larvicidal activity	[106]
Ni NPs	*Terminalia chebula* fruit aqueous extract	*E. coli*, *K. pneumonia*, *B. subtilis*, and *S. aureus*	Anticancer, antibacterial, and antioxidant activity	[107]
Ni NPs	*Z. officinale* rhizome extracts	*P. aeruginosa*, *E. coli*, *P. vulgaris*, and MCF-7 cells	Antibacterial, anticancer, antioxidant, antiparasitic, and antidiabetic	[108]
Zr NPs	*Punica granatum* peel extract	*B. subtilis*, *S. aureus*, *E. coli*, *K. pneumonia*, and *A. niger*	Antimicrobial, antioxidant activity	[109]

potential antimicrobial activity and effective against several microbes, including fungi, bacteria, algae, and viruses [118]. Plant-mediated Ag NPs have been used for the treatment of dental infections because they contain antifouling, antimicrobial, and remineralizing properties [119]. Many plant extracts such as *Ficus racemosa*, *Azadirachta indica*, *Eclipta prostrate*, *Feronia elephantum*, and *Agave sisalana* were utilized to synthesize Ag NPs which have been reported as a biocontrol agent against mosquitos and also show larvicidal activity against larvae of *Ades aegypti*, *Anopheles stephensi*, and *Culex quinquefasciatus* [120, 121]. Scientists experimented on inhibition circles and investigated growth curves against *C. albicans* (Gram-positive) and *E. coli* (Gram-negative) to determine the antibacterial activity of synthesized Ag NPs. The result showed positive antibacterial activity. Novel Ag NPs synthesized using an extract of *Ilex paraguariensis* were reported as potent bactericidal agents against tested pathogens *B. cereus*, *P. aeruginosa*, and *S. aureus* [122]. Drugs creating resistance against microorganisms is one of the common reasons for global demand to synthesize novel Ag NPs which must be potent against multi-drug-resistant microorganisms. Various studies address the activity of Ag NPs in drug delivery, antiulcer, antiparasitic, wound healing properties, etc. [123]. Literature reported many medicinal herbs have been used to synthesize Ag NPs such as *Allium sativum*, *Zingiber officinale*, *Morinda citrifolia*, *Piper nigrum*, *Tinospora cordifolia*, *Tephrosia tinctoria*, *Gloriosa superba*, *Calotropis gigantea*, *Hemidesmus indicus*, *Moringa oleifera*, and *Aristolochia indica*. [124]. Another ecofriendly synthesized Ag NPs by utilizing leaf extract of *Tropaeolum majus L.* was reported as antimicrobial including antifungal, antibacterial, antioxidant, and anticancer activity [125]. Leaf extract of the herbal plant *Holoptelea integrifolia* was investigated as having potent antidiabetic, anti-inflammatory, antioxidant, and antibacterial activity against *E. coli* and *S. typhimurium* [126]. Aqueous extract of leaf was used to synthesize simple and eco-friendly Ag NPs that have shown strong anticancer activity, antioxidant activity, and larvicidal activity [127]. Based on green nanotechnology number of herbal plants were reported and some are under research. Various plants were reported to synthesize Ag NPs such as *Anacardium occidentale*, *Astragalus gummier*, *Carica papaya*, *Andrographis paniculata*, *Citrullus colocynthis*, *Datura metal*, *Dioscorea bulbifera*, *Elettaria cardamom*, *Glycyrrhiza glabra*, *Hibiscus cannabinus*, *Lomri herba*, *Morinda pubescens*, and *Piper betel* [128]. *Nauclea latifolia*, *Cynara scolymus*, *Ananas comosus*, *Malus domestica*, *Ocimum sanctum*, *Cassia auriculata*, *Ficus benghalensis*, *Citrus sinensis*, *Alfalfa sprouts*, *Argemone mexicana*, *Ceratonia siliqua* [129]. Ag NPs were synthesized using leaf extract of the purple heart plant and evaluated as an antibacterial agent against *S. aureus* and *E. coli*. Recently some studies have reported that the conjugation of bactericidal agents with Ag NPs may cause a reduction of toxic effects in mammalian cells and enhance bactericidal activity. This conjugation improves the therapeutic effectiveness of antibiotics against bacterial infections because it increases the number of antibacterial agents on the site of infections [130]. The study revealed the antidiabetic and antibacterial activity of synthesized Ag NPs produced with leaves extract of *Allium fistulosum*, *Basella alba*, and *Tabernaemontana divaricate* [131]. These were strongly effective against both Gram-positive and Gram-negative microorganisms. Another study reported cytotoxicity assay of the synthesized Ag NPs by utilizing *Solanum melongena* leaves extract revealed a viability percentage of 50.23 at 100 μg/ml. The synthesized Ag NPs triggered early apoptosis in a larger percentage of MDA-MB-231 cell lines and also showed antibacterial activity against tested bacterial isolates such as *E. coli*, *K. pneumoniae*, *S. flexneri*, *P. aeruginosa*, *P. vulgaris*, and *S. aureus*. The highest mortality was found at 100 μg/ml concentrations [132].

7.1.2. Au NPs. Au is a soft, highly malleable, and ductile yellow color metal, which is so costly for so many reasons even though many people are attracted to this due to its golden shiny appearance [133]. Nowadays, Au is widely used in the biomedical field for synthesizing Au NPs as nanobiotechnology pays attention to the therapeutical treatment of various diseases. The surface area of Au is great due to its small particle size and is used in biosensing, catalysis, and bioimaging [134]. Recently researchers focused on the synthesis of NPs utilizing various plant extracts; hence, Au NPs were synthesized as they are biocompatible, economical with lesser side effects, and consist of unique properties [135]. Au NPs are used in biosensing [136], electrochemical sensors [137], photothermal treatment, immunochemical research to determine protein interaction, DNA fingerprinting, drug delivery, antibacterial [138], cancer diagnosis [139], anticancer [140], antimicrobial, antioxidant [141], neurological diseases, retinopathy, cartilage disorders, skin disorder, cardiovascular diseases, and metabolic syndrome [142]. Au NPs have a wide array of applications in other fields too such as food safety, water treatment, fabrics, chemistry, and photo-catalysis so researchers synthesized them with interest via three synthesis methods: chemical synthesis, physical synthesis, and biological synthesis [143]. Biological synthesis has gained attention due to its cost-effectiveness, fewer side effects, and environmental friendliness. Plant-mediated Au NPs have bactericidal properties and kill them via structural modification. The atomic number of Au NPs is high due to this, it is used for radiotherapy sensitization, cancer diagnosis, and the treatment of tumors [144]. Plants such as *Ricinus communis* have recently been used for the production of Au NPs. *Dracocephalum kotschyi*, *Camellia sinensis*, *A. occidentale*, *Euphorbia peplus*, *Euphorbia Fischer Diana*, and *Musa acuminata Colla* have been studied and reported. Many researchers synthesized Au NPs by utilizing plant extracts in their experiments which are effective against bacteria [145–149]. The body synthesizes antibodies against many diseases like chronic inflammation, and autoimmune disease in cancer treatment when the immune system is activated. Scientists reported that Au NPs were synthesized by using bacteria, fungi, bioextracts, and plant extracts such as *Diospyros kaki*, *Magnolia kobus*, *Shewanella oneidensis*, and *Yarrowia lipolytic*, which played an immense role in enhancing the body's immune system during cancer therapy and removes inflammation [150]. A study revealed that Au NPs utilizing *Hygrophila spinosa* leaf extract showed anticancer, antibacterial, and antifungal activity against several tested pathogens [151]. NPs are used widely in drug delivery for asthma patients [152].

Synthesized *Olea europaea* Au-mediated NPs inhibited the formation of biofilm in bacterial strains (Gram-positive and Gram-negative) and further investigation proved that it inhibits essential proteins of the cell wall in targeted *S. aureus*. In addition, these NPs showed excellent cytotoxicity and were active against MCF-7 cancer cells [153]. Scientists reported that chitosan-based Au NPs were synthesized as nanocarriers to improve insulin uptake via an oral route [154, 155]. Au NPs were prepared using black tea extracts and were tested against the HCT116 colon cancer cell line and as a result, they were found as excellent anticancer activity via ROS generation and apoptosis [156]. Studies demonstrated Au NPs prepared from leaf extract of *Syzygium cumini* and *Sargassum muticum* (brown seaweed) tested on various cancer cell lines exhibited excellent anticancer activity [157].

7.1.3. Co NPs. Co is vital to all animal metabolism due to its function in cobalamin, the principal biological reservoir of Co as an ultratrace element. Co NPs have piqued the interest of researchers due to their novel uses in fields such as photocatalysis, antimicrobial activity, and electrochemical sensing [158]. In recent years, a large amount of research has been undertaken on the improvement of Co NPs characteristics utilizing a plant-mediated green synthesis strategy. The green Co NPs was produced by utilizing methanolic leaf extract of *Trianthema portulacastrum L.* and reported as a potent antibacterial activity against *E. coli* as compared to *B. subtilis* [159]. The medical plant *O. sanctum* (Tulsi) was used to prepare 110 nm, crystal-shaped Co NPs and evaluated anticancer properties against MDA-MB-231(breast cancer) cell line [160]. Another scientist reported cytotoxicity activity of green synthesized Co OH NPs by using aerial parts of *Lantana camara L.* extract against HCT-116 cancer cells with an IC_{50} value of 25 μg/ml and found reduction in cytotoxicity toward noncancerous VERO cells having an IC_{50} value of 200 μg/ml, implying that the particles have selective anticancerous cytotoxicity [161].

7.1.4. Cu NPs. The stem bark of *Annona squamosa L.* was utilized to synthesized 13.7 ± 3.3 nm Cu NPs, evaluated for antibacterial activity and reported inhibition zones were 12.3, 13.9, 15.7 mm against *C. albicans*, *E. coli*, *and S. aureus*, respectively [162]. In another report, Cu NPs were synthesized by using stem extract of *Hippophae rhamnoides L.* (Himalayan plant). Further, the researcher investigated dose-dependent anticancer activity of synthesized Cu NPs against Hela cancer cell lines via MTT assay and reported decrease in cell viability at 100 μg/ml with an IC_{50} value was 48 μg/ml [163].

7.1.5. Fe NPs. Green synthesis of Fe NPs is a fascinating study topic that has gained prominence due to the reliable, sustainable, and ecofriendly methodology for synthesizing NPs, as well as the simple availability of plant materials and their medicinal significance. Magnetic Fe NPs have significant importance due to their magnetic property, catalytic activity for the removal of pollutants from water bodies, and remarkable antibacterial and antioxidant activity. Many researchers have reported the production of Fe NPs from various plant sources which have been studied for antibacterial and anticancer activities. Fe NPs have an unfavorable effect on cell viability, division, and metabolic activity [164]. Novel Fe NPs were prepared by using *Arabic coffee* and investigated their anticancer and cytotoxicity activity against selected lung cancer cell lines (HT144, SKMEL2, and WM266-4) via MTT assay and found to be potent anticancer action with an IC_{50} were 273, 216, and 250 μg/ml against the tested cell lines, respectively [165]. Leaves extract of *Vitex leucoxylon* were utilized to synthesized crystalline Fe NPs having 136.43 nm diameter evaluated for anticancer activity against KB-3-1(oral), A549 (lung), and A375 (skin) cancer cell lines via MTT assay [166].

7.2. Antibacterial and Anticancer Action of Green MONPs. Numerous reports suggested that the metal oxides that were used extensively to develop green MONPs are Bi_2O_3, CeO_2, Co_3O_4, $CoFe_2O_4$, CuO, Fe_2O_3, NiO, TiO_2, ZnO, ZrO_2, etc. These green MONPs possess excellent antibacterial and anticancer activities, as shown in Table 2.

7.2.1. Co_3O_4 NPs and $CoFe_2O_4$ NPs. Co_3O_4 NPs are transition metal oxides with magnetic p-type semiconductors and intriguing catalytic characteristics. Co O, Co_2O_3, and Co_3O_4 are the three principal oxidation states of Co-based NPs. Because of the surface effects and changing oxidation state of Co, the Co_3O_4 NPs have been widely studies against bacterial infections and for cancer treatments. The extract of *Sena auriculata* flower was used to synthesized green Co_3O_4 NPs which showed excellent antibacterial and antifungal activity against tested bacterial and fungal species such as *S. aureus*, *S. mutans*, *K. pneumonia*, *E. coli*, *A. flavus*, and *A. Niger* under in vitro environment. The zone of inhibition found to be in the range from 20 ± 0.42 to 33 ± 0.67 mm and 22 ± 0.61 to 26 ± 0.81 mm for all fungi and bacteria, respectively [216]. The leaves of *Curcuma longa* were used to produced 26 nm size green Co_3O_4 NPs which showed potent antibacterial activity against the tested species of *E. coli* and *S. aurues* [217]. According to the research, $CoFe_2O_4$ doped with metal ions such as Mn^{+2} is gaining popularity in a variety of applications, particularly biomedical applications. $CoFe_2O_4$ magnetic NPs have a strong coercivity and a moderate magnetism. The researcher reported excellent invitro anticancer and antibacterial activity of 12 mm size synthesized CFNPs and CFM NPs via hydrothermal method by utilizing *Swertia Chirata* ethanolic extract as a reducing agent [218]. An ecofriendly spherical shape, 80 nm size Co_3O_4 NPs were synthesized by utilizing *Phoenix dactylifera* (date palm) seed extract responsible for potent antibacterial activity against the Gram-positive and Gram-negative bacteria such as *B. subtilis*, *S. aureus*, *K. pneumoniae*, and *E. coli*, respectively [219]. A unique biogenesis of Co_3O_4 NPs was achieved utilizing Arishta leaves extract at various annealing temperatures such as 200, 400, 600, and 800°C. Due to higher concentration of flavonoids and polyphenolic components in Arishta leaves, synthesized Co_3O_4 NPs were effective against bacterial species like *S. aureus*, *S. mutans*, *K. pneumonia*, and *E. coli* as well as fungal species *A. flavus* and *A. Niger* [220]. The seed extract of *Caccinia macranthera* was utilized to produce novel green Co_3O_4NPs and studied for anticancer activity [221]. Aqueous extract of

Table 2: Biological activity of green synthesized MONPs.

Synthesized NPs	Plant extract/method used	Tested pathogens/cells	Biological application	References
Ag and Cu doped Bi_2O_3 NPs	*Biebersteinia multifida* extract	*P. aeruginosa*, *S. aureus* and U87, 3T3 cancer cell lines	Antibacterial, anticancer activity	[167]
δ-Bi_2O_3 NPs	*Crinum viviparum* flower extract	Inhibition of protein (NDM-1) PDB ID 5XP9	Photocatalytic dye degradation	[168]
CeO_2 NPs	*Cannabis sativa L.* extract	*S. enteridis*, *E. coli*, *B. subtilis*, *S. aureus*, and MCF7, MDA-MB-231, hTERT-HME1 cancer cell lines	Antimicrobial, anticancer activity	[169]
CeO_2 NPs	*Scoparia dulsis L.* extract	A549 cancer cell line	Anticancer activity	[170]
CeO_2 NPs	*Polygonum bistorta L.* root extract	*L. tropica*	Bactericidal, antioxidant activity	[171]
CeO_2 NPs	*Acacia concinna* fruit extract	*S. pneumoniae* and *E. coli*	Antimicrobial activity	[172]
Ce-doped Bi_2O_3	*Pilea microphylla* leaves extract	Water splitting	Electrocatalyst activity	[173]
Co-doped Bi_2O_3	*A. sativum L.*	*B. subtilis*, *S. epidermidis*, *E. coli*, *P. aeruginosa*, *C. albicans*, *C. krusei*, and HepG2, A549 cancer cell lines	Antimicrobial, anticancer activity	[174]
Co-doped ZnO NPs	*Prosopis fractal* leaves extract	*S. aureus*, *E. coli*, and MCF7 cell line	Antimicrobia, cytotoxicity activity	[175]
CuO NPs	*Padina boergesenii*	*B. subtilis*, *E. coli*, and A375 cancer cells	Antibacterial, anticancer activity	[176]
CuO NPs	*B. monnieri* leaf extract	*H. bizzozeronii*	Antibacterial, antidiabetic, anti-inflammatory activity	[177]
CuO NPs	*Spirulina platensis* (blue green algae)	A549, HCT, and Hep2 cell line	Anticancer activity	[178]
Cu-doped NiO NPs	*Cullen tomentosum* plant extract	*B. subtilis*, *S. pneumoniae*, *K. pneumoniae*, *E. coli*, *and* MDA-MB-231 cell line	Antibacterial and Anticancer activity	[179]
FeO NPs	*Curcumin* extract	*E. coli*, *K. pneumoniae*	Antibacterial activity	[180]
MgO NPs	*A. sativum L*	*S. epidermidis*, *E. coli*, *C. albicans*, and HepG2, A549 cell lines	Anticancer activity	[181]
MgO NPs	*Mangifera indica*, *A. indica* and *C. papaya* leaf extracts	*E. coli*, *S. aureus*, and *P. aeruginosa*	Antibacterial activity	[182]
NiO NPs	*Cleome simplicifolia* leaves extract	DZNU-Bm-17 and *Labeo rohita* liver cells	Cytotoxicity study	[183]
NiO NPs	*Elaeagnus angustifolia*	HUH7 and HEP-G2 cancer cells	Anticancer activity	[184]
NiO NPs	*Marsdenia tenacissima* leaf extract	A549 and H1299 cancer cells	Anticancer activity	[185]
NiO NPs	*Sesbania grandiflora* flower extract	MM2 and HeLa cancer cells	Anticancer activity	[186]
TiO_2 NPs	*L. acutangula*	*E. Coli*, *P. aeruginosa*, *S. aureus*, *K. pneumoniae*, *E. faecalis*, and *B. subtilis*, *S. rolfsii*	Antibacterial, antifungal, and antimicrobial activity	[187, 188]
B-TiO_2 NPs	Sol–gel process (flask shaking method)	*S. aureus*, *E. coli*, and *C. albicans*	Antibacterial, bactericidal activity	[189]
TiO_2 NPs	*M. fragrans* seed extract	*S. aureus* and *K. pneumonia*	Photocatalytic activity, antibacterial property	[190]
TiO_2 NPs	Laser ablation	*E. coli* and *S. aureus*	Antibacterial activity	[191]
TiO_2 NPs	Combined with antibiotic	*P. aeruginosa*	Antibacterial activity	[192]
TiO_2 NPs	Iranian propolis extracts	Oral bacteria and fibroblast cells	Antimicrobial activity	[184]
Ag-doped TiO_2 NPs	Calcination and Electrospinning method	*S. aureus* and *S. albany*	Antibacterial activity	[193]
TiO_2 NPs	Fruit peel	*E. coli*, *S. aureus*, *P. aerugenosa*, and *B. Subtilis*	Antibacterial, antioxidant activity	[194]
TiO_2 NPs	*A. indica*	*E. coli*, *S. typhi*, *B. subtilis*, and *K. pneumoniae*	Antimicrobial activity	[195]
TiO_2 NPs	Guar gum	*E. coli* and *S. aureus*	Wound healing activity	[196]
TiO_2 NPs	Sonochemical process	*P. aeruginosa*	Antibacterial and antiviral activity	[197]

Table 2: Continued.

Synthesized NPs	Plant extract/method used	Tested pathogens/cells	Biological application	References
TiO_2 NPs	Electrochemical method	*E. coli* and *S. aureus*	Antibacterial activity	[198]
r-GO/TiO_2 NC	*Moringa olefera* stick extract	DPPH	Radical scavenging activity	[199]
ZnO NPs	Fennel seeds extract	*Cryptococcus* sp., *S. aureus*, *P. aeruginosa*, *C. parapsilosis*, and MCF-7 cells	Antitumor activity	[200]
ZnO NPs	*Desertifilum* species (cyano bacterium strain)	*S. aureus*, *E. coli*, and *P. aeruginosa*	Antibacterial, anticancer, and antibiofilm activity	[201]
ZnO NPs	Peel of *P. granatum* and chemical synthesis	*S. aureus*, *K. pneumonia*, and *P. aeruginosa*	Antibacterial, cytotoxicity activity	[202]
ZnO NPs	6-pentyl α pyrone lactone (green fungal metabolite)	*Enterobacterales* sp.	Antimicrobial activity, effective against UTI	[203]
ZnO NPs	Leaf extract of *P. guajava*	*B. cereus*, *S. aureus*, *K. pneumoniae*, and *E. coli*	Antimicrobial activity	[204]
ZnO NPs	*A.* marmelos fruit extract	*C. cornuta*	Antibacterial activity, antioxidant activity	[205]
ZnO NPs	*Pongamia pinnate* leaves	*P. aeruginosa*	Antibacterial activity	[206]
ZnO NPs	*Streptomyces* sp.	*E. coli* and *B. subtilis*.	Anticancer, antimicrobial activity	[207]
ZnO NPs	*Bauhinia racemosa*	*P. vulgarus*, *E. coli*, *S. aureus*, and *K. pneumoniae*	Antibacterial activity	[208]
Au and ZnO NPs	*Fusarium chlamydosporum*	*E. coli* and *P. aeruginosa*	Antibacterial anticancer activity	[209]
ZnO NSs	*Aspidopterys cordata* leaf extract	*P. vulgaris*, *E. coli*, *K. pneumonia*, and *S. aureus*	Antibacterial, antioxidant activity	[210]
ZnO and MgO	*Z. officinale* and *Glycyrrhiza* roots extract	*S. aureus*, *B. subtilis*, *L. innocua*, *P. aeruginosa*, and *S. typhimurium*	Antibacterial activity	[211]
rGO ZnO NH	*Clerodendrum infortunatum* leaf extract	DPPH free radicals	Radical scavenging activity	[212]
ZrO NPs	*Annona reticulata* leaf extract	*S. enterica serotype typhi*	Antibacterial activity	[213]
ZrO NPs	*Azadirachta indicia extract*	*E. coli*, *P. aeruginosa*, *S. aureus*, *B. subtilis* *C. albicans*, and *A. niger*	Antibacterial activity	[214]
ZrO NPs	*Andrographis paniculate* leaf extract	A549 and HCT116 cancer cell lines	Anticancer activity	[215]

Grateloupia Sparsa (red algae) was used to synthesize Co_3O_4 NPs and evaluated potent anticancer activity against HepG2 cancer with an IC_{50} value 201.3 μg/ml [222].

7.2.2. CuO NPs. Cu is one of the important constituents of the human body, animals, and plants. In the human body, it is required in a minimum amount, i.e., approximately 100 mg of Cu is required by a 70 kg man, and daily, only 2–4 mg of Cu is required. The major source of Cu is food and it plays a vital role in our body in many biochemical reactions acts as a co-factor, as a defence mechanism by enhancing the immune system, and as an antioxidant. In plants, it is essential for their growth [223]. After synthesis, characterization of CuO NPs is done by various techniques such as UV, Fourier-transform infrared spectroscopy (FTIR), TEM, ZP, EDS, dynamic light scattering (DLS), Brunau–Emmet–Teller (BET), NTA, and XRD to determine surface area [224]. MBC and time kill determination was performed by a scientist to determine the antimicrobial properties of CuO NPs [225]. Leaf extract of *Bacopa monnieri* was proposed to synthesize CuO NPs. Blue-colored copper solution turning into dark gray was the confirmation sign of formed CuO NPs. Monoclinic-shaped NPs having a size of 34.4 nm were tested against many *Helicobacter species* and found to have excellent antibacterial activity. Some other biological activities were also determined such as potent antidiabetic and strong anti-inflammatory [177]. Biogenic synthesis of CuO NPs proposed by using *Cissus vitiginea* leaf extract was analyzed by XRD and evaluated significant antioxidant activity [226]. Another study focused on the synthesis of CuO NPs by utilizing leaf extract of *Eucalyptus globulus* and investigated their adsorbent property to reduce dirt and pollutants in wastewater obtained from dairy plants [193]. Spherical-shaped CuO NPs having a size of 20 nm were synthesized by using galls extract of *Quercus infectoria* and showed potential antibacterial activity against bacteria (Gram-positive and Gram-negative) [194]. Green synthesized Ag dopped CuO NPs were prepared by utilizing leaf extract of *Moringa Oleifera* and were determined as a suitable candidate for photocatalytic action [195]. Various natural sources like bacteria, fungi, algae, and plant extract were reported to synthesize CuO NPs [227]. Bark extract of pivotal plant *Rubia cordifolia* was used to produced CuO NPs and investigated against antibacterial activity. It was reported that synthesized NPs were spherical in shape with a particle size 50.72 nm and showed noticeable antibacterial action against Gram-positive and Gram-negative bacteria such as *E. coli*, *P. aeruginosa*, *S. aureus*, and *B. cereus*, respectively [228]. A few examples that proposed potential therapeutic activity are *C. papaya L.* [197], *O. europaea L.*, *Ziziphus mauritiana Lam* [189], *Cedrus deodara* [229], *Coffea arabica L.* [230], *Streptomyces* sp. [231], and *Macrocystis pyrifera L.* [232].

7.2.3. FeO NPs. According to the reports, FeO NPs have been widely used since 1990s in applications such as medicine, biotechnology, the environment, and photocatalysis. Magnetite and maghemite phases are the most common Fe oxidation states with outstanding physicochemical properties, such as high surface area, environmental compatibility, superparamagnetic, nontoxicity, and cost-effectiveness. Mainly, FeO has gained significant interest among transition metal oxides due to its exciting properties. It could be employed to test antibacterial activities due to its extended ROS [233]. Apart from being widely available and inexpensive, FeO also plays a function in a variety of biological processes, making it an appealing metal for NPs. Biological sources have emerged as an alternative to traditional methods, improving nanomaterial production through more efficient, sustainable, and suitable for the environment. Among these novel methods, green synthesis contributes to the environment with the reduction and elimination of toxic substances and hazardous wastes [234]. Green FeO NPs were synthesized by using *Egyptian Propolis* extract and showed maximum zone of inhibition (23.5 mm) against *P. aeruginosa* among the tested organisms such as *E. coli*, *P. aeruginosa*, *S. aureus*, and *Bacillus subtilis* [235]. Green synthesized novel 9 nm, round shape, FeO NPs by utilizing aqueous gum extract of Bombax malabaricum were investigated as potent antibacterial and antifungal agent against the tested microorganisms such as *B. halodurans*, *S. aureus*, *M. luteus*, *E. coli*, *A. flavus*, and *A. niger*, respectively [236]. Green coffee and clove extracts mediated FeO NPs were reported as potent antibacterial agent against *E. coli* and *S. aureus* [237]. Antimicrobial activity of FeO NPs synthesized by utilizing Centaurea solstitia leaves extract was also reported in literature [238]. Aqueous *Pleurotus citrinopileatus* (mushroom) extract was utilized to synthesized green FeO NPs. Synthesized nanorods were hexagonal in shape and very effective against selected tested bacterial species and showed maximum zone of inhibition with *S. aureus* (9.2 ± 0.1), *P. aeruginosa* (8.1 ± 0.3), *K. pneumoniae* (7.2 ± 0.3), and *B. cereus* (7.1 ± 0.2) as per report [239]. Another report suggested the fabrication of cost-effective and ecofriendly novel FeO NPs by utilizing the extracts of *Spirogyra hyalina* and *Ajuga bracteosa* and evaluated for antibacterial activity against tested bacteria. It was found that plant-mediated NPs showed superior antibacterial, scavenging activity against *E. coli* and *S. aureus* [240]. Another study reported efficient antibacterial activity of Ag NPs as compared to FeO NPs obtained from *Fusarium solani* extract. The tested bacterial species were *S. aureus*, *B. cereus*, *P. aeruginosa*, and *E. coli*. Among all *S. aureus* and *P. aeruginosa* were the most sensitive and resistant bacteria to both NPs, with MIC of 10 and 40 μg/ml, and MBC of 20 and 80 μg/ml for Ag NPs against *S. aureus* and *P. aeruginosa*, respectively. The results were poorer for FeO NPs than for Ag NPs, with MIC of 20 μg/ml for *B. cereus* and *S. aureus* and 40 μg/ml for *P. aeruginosa* and *E. coli*, with MBC of 40 and 80 μg/ml, respectively [241]. Green synthesized FeO NPs were synthesized by utilizing *Spatoglossum asperum* (brown algae) and reported for excellent free radical scavenging and anticancer activities against glioblastoma cells with an IC_{50} value 19.24 μg/ml [242].

7.2.4. NiO NPs. NiO NPs have recently received great interest in research due to their unique physical, chemical, optical, and biological properties. Considering its various uses in diverse industries, multiple physicochemical and biological approaches have been utilized to synthesize NiO NPs [243]. Ni-containing NPs have been demonstrated to be biocompatible and chemically stable. According to the reports, NiO

NPs exhibit enhanced bactericidal properties. A CdO-NiO-ZnO NPs was also found to be antibacterial against Gram-positive and Gram-negative bacteria. Another material with high antibacterial action is NiO-CuO-10% reduced graphene oxide. NiO NPs produced by green synthetic approach are the most popular currently due to lesser side effects and potential activity against bacteria and certain types of cancers. Study reported green NiO NPs were produced by utilizing *Syzygium aromaticum* extract which showed efficient antibacterial activity against *S. aureus* in comparison to *E. coli* [244]. A bacterium *S. marcescens* produces prodigiosin pigments, used to produce NiO NPs having diameter 41.77 mm were tested against *P. aeruginosa* and showed excellent antibacterial activity [245].

7.2.5. TiO_2 NPs. TiO_2 NPs synthesized by plants extract have some distinguishing characteristics when compared to TiO_2 NPs synthesized via chemical or physical methods. For example, plant-mediated TiO_2 NPs are utilized in biomedicine, particularly for anticancer activity, they must be biocompatible with the host in order to avoid toxicity in the host cell, which is rather common in chemically or physically synthesized TiO_2 NPs [246]. The leaf extract of *Luffa acutangula* was utilized to produced TiO_2 NPs and showed potent antimicrobial, antifungal, and antibacterial activity against several tested pathogens at higher concentration. The maximum zone of inhibition was found, at a concentration of 40 mg/ml for *E. coli*, i.e., 45 ± 0.21 and 43 ± 0.45, 42 ± 0.13, 27 ± 0.54, 21 ± 0.41, and 18 ± 0.56 for *P. aeruginosa*, *S. aureus*, *K. pneumonia*, *E. faecalis*, and *B. subtilis*, respectively. MIC was found at a concentration of 5 μg/ml against *E. coli*. Another study reported excellent antifungal activity for TiO_2 NPs against *S. rolfsii*, i.e., 42 ± 0.25 which was determined by the maximum zone of inhibition [187]. Javed et al. [247] focused on the multifunctional approach of TiO_2 NPs as they are widely used in the medical field such as potent antimicrobial, tissue regeneration, and agriculture nanobiotechnology through the formation of nanofertilizers and nanopesticides. Duman and Bulut [248] synthesized TiO_2-PVA and Ag-doped TiO_2 nanocomposite powders by sol–gel process and investigated their antibacterial activity against *S. aureus* and *E. coli*. Researchers found that the antibacterial effect was more on *S. aureus* as compared to *E. coli*, i.e., around 105 CFU. Wang et al. [249] found antibacterial activity and bactericidal activity in the synthesized B-TiO_2 NPs by sol–gel process. The flask-shaking method was used to determine the bactericidal effect against *S. aureus*, *E. coli*, and *C. albicans*. The researcher found that the zone of inhibition was clearer for the B-TiO_2 NPs and killed *S. aureus* more effectively than the other two bacteria [249]. By following green approach, *Myristica fragrans* plant extract acts as a reducing agent and helps in the production of TiO_2 NPs that show superior photocatalytic activity. It was determined based on the degradation capacity of dye's solution such as congo red and methylene blue, i.e., 99% in 45 min and 97% in 60 min, respectively. This study also revealed the antibacterial properties of two bacteria such as *S. aureus* and *K. pneumonia* with a minute inhibition difference, i.e., 79% and 72%, respectively [190]. Another researcher prepared coated TiO_2 NPs on cotton fabrics in different concentrations that showed antibacterial at 50 mg concentration against *Shigella* [250]. In a particular study, it was found that multiple strains of *P. aeruginosa* created drug-resistant against many antibiotics so they focused on drug combination therapy as a new antibacterial agent. The researcher synthesized and combined TiO_2 NPs with antibiotics, checked their efficiency, and observed excellent antibacterial activity against 25 isolates of *P. aeruginosa* which were highly resistant to cefepime, ceftriaxone, amikacin, and ciprofloxacin [192]. Another scientist synthesized Ag-doped TiO_2 NPs by calcination and electrospinning method. Different concentrations of Ag were used to coat TiO_2 nanofibers to enhance the antibacterial activity against various bacteria both Gram-positive and Gram-negative. Deterioration was found in fiber diameter at 1% concentration of Ag, i.e., 8.9 ± 22.8. nm. Maximum reduction was observed at a 2% concentration of Ag loading against *S. aureus* and *S. Albany* bacteria, i.e., 1.38 ± 0.07 CFU $99 + 9$ and 5.92 ± 0 CFU [251]. In green synthesis, fruit and vegetable peel extracts are also utilized for obtaining novel plant-mediated NPs. Peel of fruits such as kiwi, plum, and peach was utilized to synthesize cylindrical TiO_2 NPs having size ranges from 47.1 up to 200 nm, represented dose-dependent antioxidant and antibacterial activity against tested pathogens such as *E. coli*, *S. aureus*, *P. aerugenosa*, and *B. subtilis* [252]. Leaf extract of *A. indica* was used to synthesize TiO_2 NPs exhibited effective antimicrobial activity. The spherical shape NPs having a size between 15 and 50 nm showed antibacterial activity against various tested pathogens, such as *E. coli*, *S. typhi*, *B. subtilis*, and *K. pneumonia*. The least MIC was found against *E. coli* and *S. typhi*, i.e., 10.42 μg/ml, and the lowest MBC was found against *K. pneumonia*, i.e., 83.3 μg/ml [253]. Another researcher performed an in vivo and in vitro study of the synthesized TiO_2 NPs by utilizing guar gum and found it to be effective for wound healing. In vitro studies were performed on 3T3 fibroblast cells of mice and in vivo study was performed on open excision wounds model using Sprague Dawley rat. The researcher also found excellent antibacterial properties against *E. coli* and *S. aureus* with an exhibition zone of 11 ± 0.06 and 9 ± 0.25 mm, respectively [254].

7.2.6. ZnO NPs. Zinc is an essential inorganic nutrient present in all enzymes in the living system, viz., oxidoreductase, transferase, ligase, lyases, isomerases, and hydrolases, and possesses excellent catalytic activity in body metabolism [255]. ZnO NPs of different sizes and shapes were formed by various physical, chemical, and biological methods showed excellent antimicrobial properties and were also used as a feed supplement for animals [256, 257]. Synthesized ZnO NPs are highly effective against pathogens (broad spectrum) and attain great potential as an antimicrobial agent [258, 259]. Ebadi et al. [201] synthesized 88 nm size ZnO rod-shaped NPs using *Desertifilum* species (*cyano bacterium* strain) and showed the highest antibacterial activity against *S. aureus* in comparison to, *E. coli*, and *P. aeruginosa*. The MIC of synthesized ZnO NPs were 1,500, and 2,000 at 32 μg/ml, and MBC values were 2,500, 3,500, at 64 μg/ml. The anticancer activity of

synthesized NPs shows less toxicity toward MRC-5 lung cancer cells at a concentration of 100 μg/ml. The researcher also found antibiofilm activity which was determined by confocal laser scanning microscopy [201]. Abdelmigid et al. [202] used coffee ground extracts and peel of *P. granatum* for the synthesis of novel ZnO NPs as a reducing agent and capping agents in contrast also synthesized ZnO NPs chemically by using sodium hydroxide and zinc acetate dihydrate. Chemically synthesized ZnO NPs showed potent antibacterial action against *S. aureus*, *K. pneumonia*, and *P. aeruginosa*. The cytotoxicity effect of ZnO NPs using coffee ground extracts from *Punica* peel was lower than that of chemically synthesized ZnO NPs the IC_{50} value of chemically synthesized ZnO NPs was 111, 103, and 93 μg/ml against vitro cells [202]. Kotb et al. [203] focused on multidrug-resistant *Enterobacterales* sp. which is the major cause of urinary tract infections. It was found that 6-pentyl α pyrone lactone (green fungal metabolite) showed antibacterial activity against *Enterobacterales* sp. and when combined with ZnO NPs gave promising results to overcome the resistance in UTI. The human urine samples were collected, and around 57.27% of samples were found positive for *Enterobacterale* sp. The MIC value was found to be 16–32 μg/ml for 6-pentyl-α-pyrone lactone and reasonable antimicrobial action was obtained but for ZnO NPs, the MIC value was in the range of 0.015–32 μg/ml and showed excellent antimicrobial effect [203]. Ramya et al. [204] used the sol–gel irradiation technique to synthesize novel ZnO NPs and capped them with leaf extract of *Psidium guajava*, and investigated them against some bacterial strains. These synthesized ZnO NPs are rod-shaped having a size of 15.8 nm. Zone of inhibition for antimicrobial activity against *B. cereus*, *S. aureus*, and *K. pneumonia*, *E. coli* was found in the range of 22–14 nm [204]. Senthamarai and Malaikozhundan [205] synthesized stabilized ZnO NPs using unripe fruit *A. marmelos* extract. The researcher found great antibiofilm and antibacterial activity of synthesized ZnO NPs against Gram-negative bacteria. Antioxidant action was also determined at a concentration of 100 μg/ml (increased H_2O_2 inhibition up to 88%). In total, 100% mortality was found against tested organisms, i.e., *C. cornuta* at 125 mg/l [205]. Ghosh et al. [206] synthesized ZnO NPs from *Pongamia pinnate* leaves to treat the infection that occurred from this dangerous pathogen *P. aeruginosa* as it creates resistance toward antibiotics. The synthesized ZnO NPs and antibiotics showed a synergistic antibacterial effect against this pathogen with an inhibition zone of 38 mm [206]. In another article, spherical shape ZnO NPs by using dry and fresh alhagi extracts having size ranges from 40–100 to 25–100 nm, respectively, were effective against cancer cells and act as an excellent antibacterial, and antifungal based on obtained results [260]. Another scientist synthesized and characterized ZnO NPs by utilizing the *B. foraminis* strain and ZnO. ZnO was used in this research due to its potent antibacterial activity. After synthesis further characterization was done through UV, TEM, FTIR, and determined spherical shape NPs having a size range of 5.40–6.79 nm [188]. Another spherical shape ZnO NPs by using *Aspergillus niger* having a size range between 84 and 91 nm. The synthesized ZnO NPs showed a dual role, as a nanomedicine or also used in the agrochemical industry. They showed excellent catalytic activity which is used in degrading Bismarck brown dye via the mineralization process (in wastewater treatment). ZnO NPs also showed potent antimicrobial activity upon incorporation over cotton fabrics [261]. The biologically synthesized spherical shape ZnO NPs by utilizing *Streptomyces* sp. showing potent anticancer and antimicrobial activity. Synthesized NPs having sizes 20–50 nm showed IC_{50} value $-15.61\,\mu g\,mL^{-1}$ and found anticancer activity against A549 lung cancer cells. The antimicrobial activity was evaluated against *E. coli* and *B. subtilis*. Maximum zone of inhibition against *E. coli*. species was found at 12 mm at 100 μg/ml concentration [207].

7.2.7. ZrO_2 NPs. ZrO_2 NPs are a gray-white and lustrous metal that have sparked considerable interest in biomedical and environmental studies due to their optical, electrical, thermal stability, microbial resistance, and strong corrosion resistance properties. In recent years, there has been a rise in the production of ZrO_2 NPs [262]. The potential of ZrO_2 NPs to generate free oxygen radicals is also advantageous in cancer treatment. In biological system, the oxidative metabolism generates ROS, which operate as a secondary messenger in a variety of physiological pathways, including cell survival. The body's natural antioxidant defence mechanism is always at work, scavenging ROS by binding to and neutralizing free radicals. However, producing ROS over the physiological threshold activates controlled cell death processes, which can be used in a variety of cancer treatments [263, 264]. Previously reported research indicated that the ROS pathway was required for ZrO_2 NPs to cause cytotoxicity in a variety of cancer cell lines including A549, HCT116, and MCF7 [265]. Study reported that synthesized ZrO_2 NPs by utilizing *Parkia biglandulosa* leaf extract were found to be a potent bactericidal agent when tested against *L. acidophilus*, *S. albus*, and *S. mutans* and anticancer agent when tested via MTT assay against MCF-7 (breast cancer) cell lines [266]. Aqueous leaf extract of *Andrographis paniculate* was utilized to produced ZrO_2 NPs on the flattened rough surface of reduced graphene oxide (ZrO_2/rGO) nanocrystals. Further, the anticancer activity of the synthesized ZrO_2/rGO was tested on two human cancer cell lines (A549 and HCT116) as well as hMSC (one normal human cell line) via MTT assay and found it trigger apoptosis and dose-dependent cytotoxicity in both cancer cell lines [215]. Plant extract of *Murraya koenigii* was utilized to produce ZrO_2 NPs and evaluated for antibacterial action against *E. coli* and *S. aureus*. Among the tested pathogens, maximum zone of inhibition was gained against *S. aureus* [267].

7.3. Antibacterial and Anticancer Action of Green BMNPs. BMNPs are made up of two different types of metals that open a wide range of applications including catalysis, agriculture, wastewater treatment and are also being researched as possible antibacterial and anticancer agents in biomedicine. BMNPs display significant plasmon resonances due to their electrical structure, which is responsible for their excellent catalytic characteristics. Furthermore, Au, Co, Fe, Ni, and Ag are the most widely employed metals in bimetallic

systems [268, 269]. BMNPs possess synergistic properties of two metals, enabling new particular applications. Due to synergistic effects and the accomplishment of various functional properties (biological, thermal, optical, catalytic, magnetic, and other features) [270], the ability of such nanomaterials to interact with cells (specifically cancer cells and inflamed tissues), their wide availability and good biocompatibility, combined with specific surface characteristics and the ability for diverse functionalization, makes them promising tools for the development of new drugs, improving the effectiveness of existing drugs, and application in clinical practice [271]. Several studies reported that plant-mediated BMNPs and MNPs have shown potential activity against cancer as well as bacterial infections. Along with different plant extracts a few researchers also utilized other natural sources like bacteria, fungi, and algae to get the desired NPs that were investigated for antibacterial and anticancer activity, as shown in Table 3. However, plants extracts were utilized more in comparison with other biological sources due to the abundance of several phytoconstituents present in them that are likely to be responsible for antibacterial and anticancer responses in tested bacterial strains and cancer cell lines. By utilizing three different plants extracts such as *Moringa oleifera*, *Mentha piperita*, and *Citrus lemon* researcher synthesized MNPs and BMNPs with the help of Ag, ZnO metal precursor, and compared their anticancer activity. Among the three extracts, *M. oleifera* showed the best anticancer efficacy for ZnO-Ag BMNPs against HeLA cancer cell lines. The observed cell viability at 2.5, 5, and 10 μg/ml concentration were 72%, 81%, and 84% within 24 hr [291]. Another study reported antimicrobial activity of Ag NPs, Se NPs, and Ag-Se BMNPs by using *Bacillus paramycoides* bacterial filtrate. The tested microbial strains were *A. brasiliensis*, *A. alternate*, *B. cereus*, *B. subtilis*, *C. albicans*, *E. coli*, *F. oxysporum*, *K. pneumoniae*, and *P. aeruginosa*. Among the tested strains, Ag-Se BMNPs showed maximum inhibitory concentration, i.e., 62.5 μg/ml, against *C. albicans*, and this strain has great susceptibility to all synthesized NPs [292]. As per reports, flower buds of *S. aromaticum* plant extract were utilized to produced Ag-Fe BMNPs which showed promising antibacterial action against *E. coli*, *P. aeruginosa*, *and S. aureus* and also exhibited good antioxidant activity [293]. Another report suggested antimicrobial and antioxidant activity of plant-mediated Zn-Cu BMNPs, Zn, and Cu MNPs. Leaves extract of *Borassus flabellifer* was utilized as an extract for development of novel Zn, Cu NPs, and Zn-Cu BMNPs attained varying sizes such as 3.0, 3.52, and 2.2 nm, respectively. The antibacterial activity findings demonstrate that Zn-Cu BMNPs were more effective than Zn, Cu MNPs. Zn-Cu BMNPs inhibited *E. coli* with the highest zone of inhibition (25 mm), *P. aeruginosa* with a zone of inhibition of 12 mm, and *S. aureus* with a zone of inhibition of 11 mm [294]. Another scientist tested antibacterial and anticancer activity of green synthesized NiO (36 nm) and Ni-CuO NPs (31 nm) utilizing *C. tomentosum* extract and found that Ni-CuO NPs showed the highest antibacterial action against Gram-positive and Gram-negative bacteria such as *B. subtilis*, *S. pneumoniae*, *E. coli*, and *K. pneumoniae*, respectively. The anticancer activity of synthesized NPs was tested against L929 (fibroblast) and MDA-MB-231 (breast) cancer cell lines and found Ni-CuO NPs have highest potency against MDA-MB-231 (breast) cancer cell line with an IC_{50} value was 11.8 μg/ml [179].

8. Mechanism of Action of Green NPs (MNPs, MONPs, BMNPs)

Green synthesis of several types of NPs by utilizing plant extracts has received great interest over the years due to its amazing antibacterial and anticancer activities. Many researchers reported that Ag NPs have excellent antimicrobial properties; hence, silver salts are combined with various plant extracts to determine their potential antibacterial action against the tested pathogens. A general representation of the plant-mediated green Ag NPs mode of action is shown in Figure 6 [295, 296].

8.1. Antimicrobial Mechanism of Green MNPs, MONPs, BMNPs. Metal-based nanoparticles can engage with bacterial envelopes and penetrate bacterial cell walls and membranes, resulting in bacteriostatic and bactericidal effects [297]. As previously stated, the smaller the size of the NPs, the better their surface/volume ratio. The increased surface/volume ratio of NPs boosts their ability to interact with diverse components of bacteria and exert antibacterial actions [298]. Ag NPs are known for their antibacterial action due to their high surface area-to-volume ratio, which allows for a greater presence of atoms on the surface and, consequently, greater contact with the environment. Furthermore, the nanosize of these particles facilitates penetration through the cell membrane, interacting with internal components, and eventually resulting in cell death throughout the multiplication process [299]. Numerous studies have demonstrated that NPs harm microorganisms by generating ROS that harm DNA, cell walls, and membranes [300]. The antimicrobial mechanism of action of plant-mediated several types of metallic NPs is described as primarily linked to the following sequence of reactions: attraction to the bacterial surface, destabilization of the bacterial cell wall and membrane, resulting in a change in permeability, dis-functioning of protein and enzyme, homeostasis of metal and metal ion disturbance, induction of toxicity and oxidative stress through the generation of ROS and free radicals, and, finally, modulation of signal transduction pathways [301, 302].

8.1.1. Generation of ROS and Oxidative Stress. Another mechanism of bactericidal activity of green NPs is the production of ROS during the interaction of metal and metal oxide with bacteria [303]. The degree of ROS formation is determined by the metal or metal oxide from which the NPs are formed, as well as the rates of ion release. When interacting with bacteria, any type of NPs (MNPs, MONPs, BMNPs) exhibits a wide spectrum of ion release and ROS formation [298]. The metal ions released by NPs have an impact on the respiratory chain and scavenging processes. As a result, singlet oxygen, hydroxyl radicals, hydrogen peroxide, superoxide anions, and other ROS are produced and accumulate. ROS can harm bacteria's internal components, including structural proteins, organelles, enzymes, DNA, the respiratory chain, and scavenging systems [304].

Table 3: Biological activity of green synthesized BMNPs.

BMNPs forms	Synthesized NPs	Extract (plant/microbe/algae/fungi)	Size (nm)/shape	Tested (pathogens/cancer cells)	Biological activity	References
Zr-based	Zr NFs	*Enicostemma littorale* plant extract	8−15 nm/tetragonal	A431 cell line	Anticancer activity	[272]
Ag-based	Ag-Au BMNPs	*Rhodopseudomonas faecalis* extract	31.71–153.7 nm	HT-29 and MCF cancer cells	Anticancer activity	[273]
Ag-based	Ag/CeO_2	*Morinda tinctoria* plant extract	21 nm and 17 nm/spherical shape	*E. coli* and *S. aureus*	Antibacterial activity	[274]
Ag-based	Ag-Cr BMNPs	*Catharanthus roseus*	30–70 nm	*S. aureus*, *E. coli*, *and E. faecalis* and HepG2 cell line	Antibacterial, anticancer activity	[275]
Ag-based	Ag-Cu BMNPs	*Salvia officinalis* leaf extract	50 nm/spherical	*K. pneumonia*, *E. coli*, *S. aureus*, and *S. epidermidis*	Antibacterial activity	[276]
Ag-based	Ag-CuO BMNPs	*C. sinensis L.* peel extract	—	*S. aureus*, *B. subtilis*, and *K. pneumonia*	Antibacterial activity	[277]
Ag-based	Ag-MNPs, $Ag-SeO_2$, and $Ag-TiO_2$-BMNPs	*Beta vulgaris L.* extract	12.82–21.28 nm, 8.417–18.49 nm, and 12.86–20.09 nm/spherical	*E. faecalis*, *S. aureus*, *E. coli*, and *S. enterica* and HePG2, MCF-7 cell line	Antibacterial, cytotoxic activity	[278]
Ag-based	Ag-Zn BMNPs	*Actinidia chinensis var. deliciosa* peel extract	—	*S. aureus*, *B. subtilis*, and *K. pneumonia*	Antimicrobial activity	—
Ag-based	Ag-ZnO BMNPs	Pomegranate peel extract	15.8 nm/round	*E. coli*, *P. aeruginosa*, *B. subtilis*, and *S. aureus* and MCF7, Caco2 cell line	Antibacterial, Anticancer activity	[279]
Ag-based	Ag-doped ZnO alloy BMNPs	*Sophora pachycarpa* fruit extract	47 nm/hexagonal	Multiple myeloma/blood cancer	Anticancer activity	[280]
Au-based	Au-Ag BMNPs	*Panax ginseng Meyer*	80.4 ± 11.9 nm/cubic	Human gastric adenocarcinoma cells	Anticancer activity	[281]
Cu-based	Cu-Ag BMNPs	*Argyreia nervosa* leaf extract	25–100 nm/irregular shapes	*E. coli*	Antimicrobial activity	[282]
Cu-based	Cu-Mg BMNPs	*Pumpkin seeds extract*	50 nm/spherical	HT-29 cell line	Anticancer activity	[283]
Cu-based	Cu-Ni BMNPs	*Peppermint leaf extract*	3–5 nm/egg shaped	*E. coli*, *S. aureus*	Antimicrobial activity	—
Pd-based	Pd-Pt BMNPs	*Nigella sativa* seed extract	5 nm	MDA-MB-231, ISH, HeLa, and L929 cell line	Anticancer activity	[284]
Pt-based	PdCo@AC BMNPs	*Cinnamomum verum* extract	2.467 nm	*E. coli*, *S. aureus*	Antibacterial activity	[285]
Pt-based	Pt-Ag BMNPs	*Hibiscus sabdariffa extract*	5.431 nm	Hydrogen production	Antimicrobial, catalytic activity	[286]
ZnO-based	ZnO-CuO BMNPs	*Artemisia abyssinica extract*	14 nm/hexagonal and monoclinic	MCF-7 cell lines	Anticancer antioxidant activity	[287]
ZnO-based	ZnO-SeO BMNPs	Pomegranate peel extract	20 nm/hexagonal shape	*E. coli*, *P. aeruginosa*, *B. subtilis*, *S. aureus*, *C. albicans*, *A. flavus*, *A. niger*, *A. fumigatus*, and Hep-G2 cell line	Antibacterial, antifungal, and anticancer activity	[288]
Se-based	Se-Ag BMNPs	Watermelon rind extract	18.3–49.6 nm/spherical and oval shapes	*C. albicans*, *E. coli*, *P. aeruginosa*, *K. oxytoca*, *B. subtilis*, *S. aureus* and MCF7 cell line	Antibacterial activity, anticancer activity	[289]
Se-based	Se-Zr BMNPs	*Cinnamomum camphora* leaf extract	100–170 nm/spherical shape	MCF-7, SK-MEL-3 cancer cell lines	Anticancer activity	[290]
Co-based NPs	$Co-Bi_2O_3$ BMNPs	*A. sativum L.*	10–100 nm/spherical shape	*B. subtilis*, *S. epidermidis*, *E. coli*, *P. aeruginosa*, *C. albicans*, *C. krusei*, and HepG2, A549 cancer cells	Antimicrobial, anticancer activity	[174]

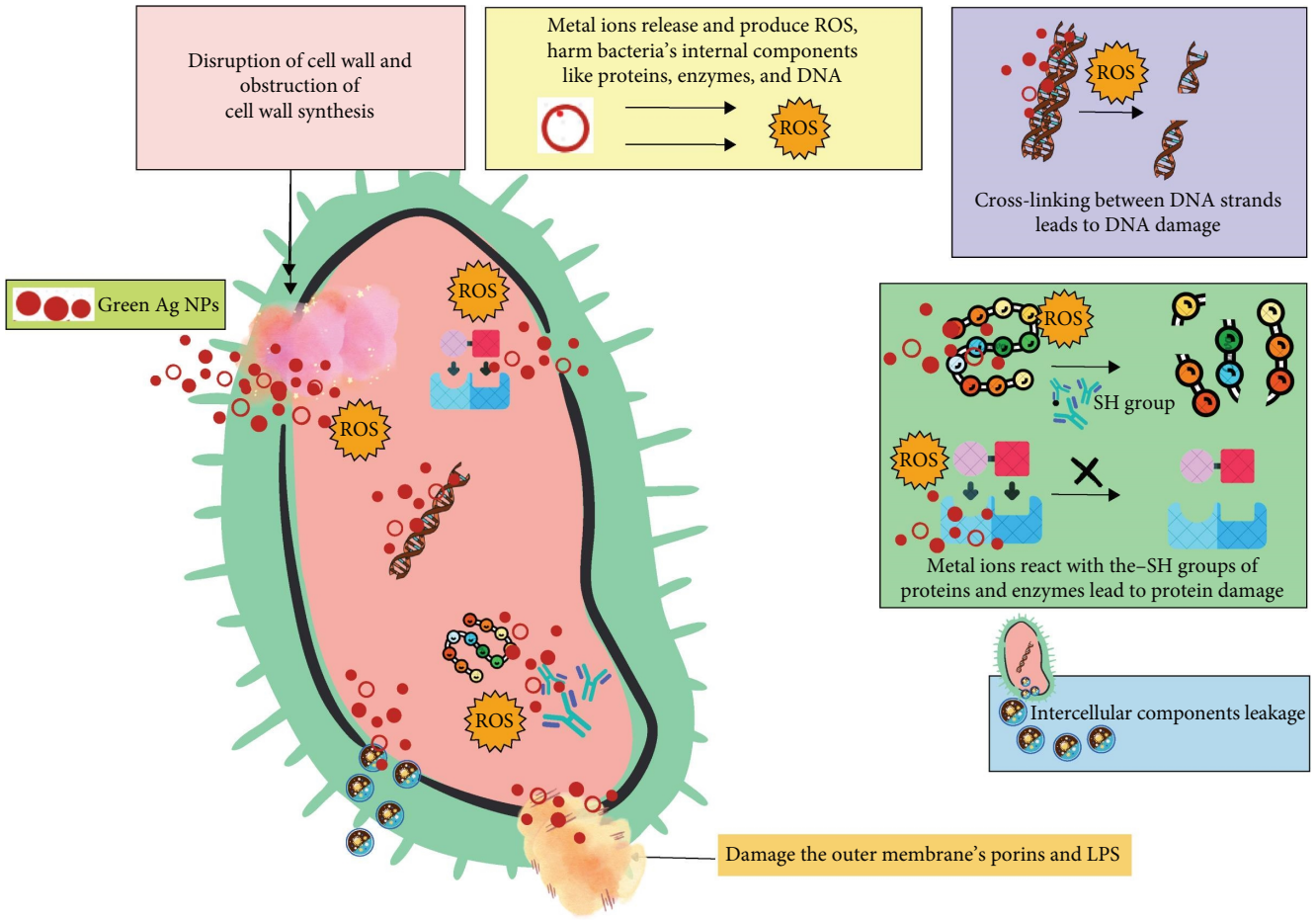

Figure 6: Antibacterial mechanism of green Ag NPs.

8.1.2. Dis-Functioning of Protein and Enzyme. Protein dysfunction is another way of antibacterial action exhibited by MNPs, MONPs, BMNPs, as shown in Figure 7 [305, 306]. The oxidation of amino acid side chains by metal ions results in protein-bound carbonyls. Carbonylation levels inside protein molecules serve as a biomarker for oxidative protein damage. Protein carbonylation causes enzymes to lose catalytic activity, ultimately causing protein breakdown [307]. Metal ions react with the –SH groups of many proteins and enzymes, rendering them inactive. Some metals, such as Ag in particular, may behave as weak acids and tend to react with soft bases such as sulfur and phosphorus, which are the key elements of proteins and DNA, respectively. Released metal ions can interact with these soft bases, causing DNA damage and cell death [308].

8.1.3. Homeostasis of Metal and Metal Ion Disturbance. For microbial survival, metal ion homeostasis is crucial because it regulates metabolic processes by helping coenzymes, cofactors, and catalysts. There will be a disruption in metabolic processes when bacteria have an overabundance of metal or metal ions. By creating cross-linking between and within DNA strands, metal ions bind to DNA and alter its helical structure [309]. Metal ions emitted by MNPs/MONPs/BMNPs have a positive charge, resulting in electrostatic interactions. Metal ions neutralize the charges on LPS and improve membrane permeability. Bacterial growth is delayed when membranes become disorganized, with increased permeability contributing to NPs buildup in the cells. For example, Ag and ZnO NPs damage the outer membrane's porins and LPS [310].

8.2. Anticancer Mechanism of Green MNPs, MONPs, BMNPs. Plant-mediated green NPs are biocompatible, environmentally benign, and can be used in drug delivery for cancer treatment. Currently, there are various cancer therapies available to treat cancer, including surgery, chemotherapy, radiation therapy, immunotherapy, photodynamic therapy, and stem cell therapy, but these therapies have many severe side effects [311]. Hence, NPs are becoming a popular tool for overcoming these challenges because NPs have a high surface-to-volume ratio, which accounts for their interaction with biological systems as atoms are freely accessible at the cell level to initiate different reactions [312, 313]. All MNPs, MONPs, and BMNPs are toxic to cancerous cell types than to normal cells. Several mechanisms have been proposed to explain the cytotoxicity mechanism of MNPs, MONPs, and BMNPs including the generation of ROS, permeation of the outer mitochondrial membrane, activation of caspase-3, as well as specific DNA cleavage, all of which led to cancer cell apoptosis, autophagy, and necrosis as shown in (Figure 8) [314, 315].

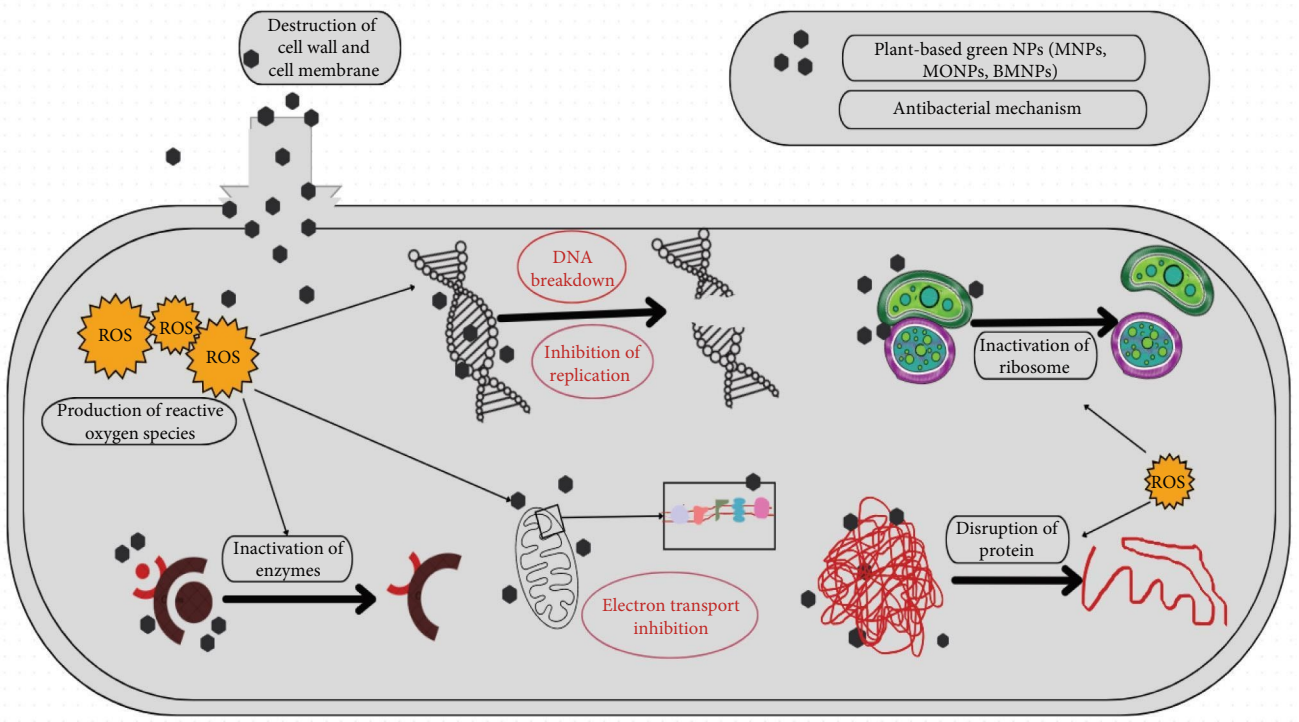

Figure 7: Plant-mediated green MNP, MONPs, and BMNPs exhibited antibacterial action by various processes involved such as ROS production leading to the destruction of bacterial cellular components, disruption of the cell wall, stopping the cell wall synthesis, breakdown of DNA, proteins, enzyme, and electron transport chain inhibition.

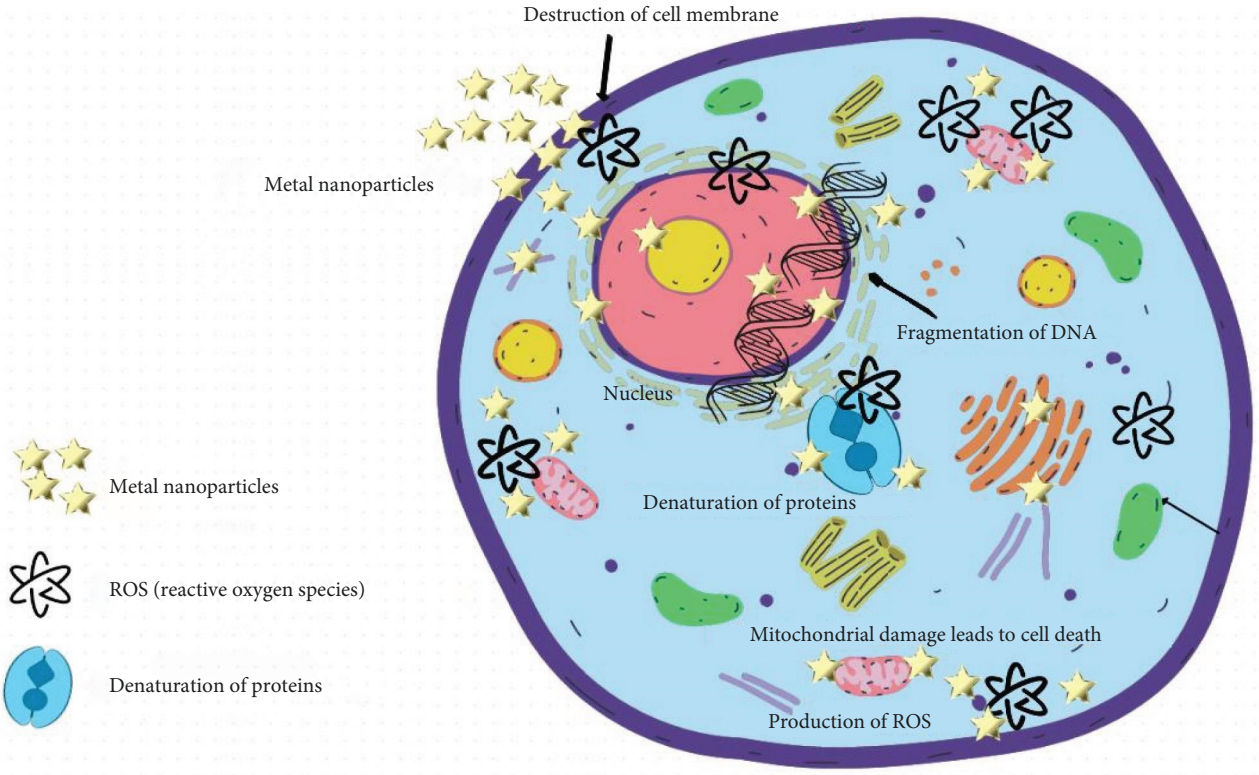

Figure 8: Diagrammatic presentation of several steps including the anticancer mechanism of green MNPs/MONPs/BMNPs against cancerous cells leading to apoptosis, autophagy, and necrosis.

8.2.1. Apoptosis. Apoptosis is a sort of programed cell death mediated mostly by caspase enzymes, which function as both initiators and executors in this process. This mechanism can be activated intrinsically (by the mitochondria) or extrinsically (via the death receptor). Intrinsic apoptosis is initiated by intrinsic stress mechanisms that are either caspase independent or caspase dependent [316]. The generated ROS causes conformational changes in the mitochondrial membrane, which results in the release of Cyt-c into the cytosol. Cyt-c is synthesized and binds to pro-caspase-8 and Apaf-1 to activate the caspase-9/3 apoptotic pathway, which initiates apoptosis by cleaving cytoplasmic and nuclear substrates PARP-1 [317]. The ligand TNF and Fas bind to death receptors, such as type 1 TNF receptor TNFR1 and Fas (CD95), which contain an intracellular death domain capable of recruiting adapter proteins like Fas-associated death domain, TNF receptor-associated death domain, and cysteine proteases. The interaction generates the death-inducing signaling complex, which signals the activation of pro-caspase-8, an initiator caspase that begins apoptosis by cleaving downstream or executioner caspases [318]

8.2.2. Necrosis. It is another type of programed cell death, which occurs when ligands such as TNF, FasL, and TNF-related apoptosis-inducing ligand bind to their respective receptors and form a complex that includes FADD, caspase-8, and RIP3. The interaction of this complex with metabolic enzymes induces the generation of ROS, which causes necrosis. During stressful conditions, other cell-death mediators/initiators such as PARP, PARP-1, RIP kinase, and calpains are also activated. The plant-based NPs stimulate RIPI3 and RIPI, which increases the production of cellular calcium and NADPH oxidase, influence mitochondria leading to ROS production and initiating programed necrosis [319]. Necrosis or apoptosis produces cellular morphological changes such as cytoplasmic shrinkage, membrane breakage, nuclear fragmentation, chromatin condensation, and structural configuration of cytoplasmic organelles, which can be detected microscopically. Both of these processes are triggered differently based on the type of cell as well as the size and dose of MNPs, MONPs, and BMNPs used [320, 321].

9. Characterization of NPs

According to the reports, once the synthesis of green MNPs, MONPs, and BMNPs has been completed, it was passed through several characterization techniques for obtaining complete information regarding the synthesized NPs such as size, shape, morphology, and the presence of functional groups, etc. The several characterization techniques that must be incorporated during the entire process are UV, FTIR, SEM, TEM, XRD, DLS, atomic force microscopy (AFM), BET, zeta potential [322], etc. The characterization details of green MNPs, MONPs, and BMNPs are given in Table 4.

9.1. UV–Visible Spectroscopy. Plant-mediated NPs are increasingly being used in various branches of science and industrial applications; however, their rapid detection and characterization at low concentration levels have remained a challenge; more specifically, there is no single technique that can characterize the physicochemical properties of NPs (composition and size) [336]. UV–vis spectroscopy is a useful technique for determining the optical activity of noble metal NPs within the range of 190–1,100 nm [337]. These NPs exhibit LSPR bands in the visible area, which are associated with the excitation of MNPs conduction electrons following their unique interaction with the electromagnetic field of light [338]. The conduction electrons in plasmonic NPs collectively oscillate to only a few wavelengths of light. As a result, they display selective photon absorption, which may be easily measured using UV–vis spectroscopy [339]. In general, the presence of a strong plasmon band near 600 nm for copper indicates that spherical Cu NPs have been formed. The colloids of ZnO NPs were formed by laser ablation of zinc bulk in distilled water at 532 nm [340]. Accordingly, absorption spectra are different for different NPs such as the absorption spectra of Ag NPs is 400–450 nm [341]. Au NPs are 500–550 nm [342], while ZnO NPs are between 350 and 390 nm [343]. Therefore, they exhibit selective photon absorption, which can easily be monitored using UV–vis spectroscopy. The scattering and absorption properties of spherical MNPs are characterized by employing the Mie theory. This theory, which was explained in 1908, can be utilized to calculate LSPRs using Maxwell's equation. The absorption spectrums of spherical and cylindrical particles are single peak and double peak, respectively [344].

9.2. Fourier-Transform Infrared Spectroscopy. FTIR is a widely used method for detecting and comparing functional groups in pure substances and mixtures. Infrared analysis is linked to the vibrational motion of atoms and molecules. Infrared light is used in the FTIR technique to identify the molecular structure of materials. This technique shows different chemical bonding in a sample or substance, detects impurities, shows oxidation and decomposition, and finds additions [345]. An FTIR commonly consists of an IR source, mirrors, a beam splitter, a detector, and a computer. The beam splitter allows the IR radiation from the source to be partially directed to two separate mirrors. The stationary mirror and the moving mirror both move at a constant speed while data are being acquired. The IR beam reflects, recombines, and passes through the sample at the beam splitter. The typical infrared wavelength that passes through the sample is 10,000–100 cm^{-1} [346]. Before reaching the detector, the radiation is absorbed by the sample and converted to rotational or vibrational energy. A computer processes the obtained data to convert the interferogram into an IR spectrum [347].

9.3. X-Ray Diffraction. XRD is one of the most comprehensive methods currently used to characterize NPs. To ascertain the crystallographic structure and morphology, including the crystalline structure, lattice parameters, type of phase, and crystalline size, XRD is a technique. The intensity might change depending on how many components are present [348]. The intensity of the diffraction changes as the atoms in the unit cell change. X-rays are electromagnetic radiation, like light. On the other hand, X-rays have a much shorter

Table 4: Characterization details of green MNPs, MONPs, and BMNPs.

Type of NPs	Plant extract used	UV–visible (nm)	FTIR	Size/shape/morphology	Biological activity	References
Ag NPs	*Pyrostegia venusta* leaf aqueous extract	381	3,355 cm^{-1} (N–H, amines/amides), 3,279 cm^{-1} (C–H, terminal alkynes), 2,930 cm^{-1} (C–H, alkanes), 2,426 cm^{-1} (O–H, carboxylic acids), 2,095 cm^{-1} (C≡C, alkynes), 1,771 cm^{-1} (C–H, aromatic), 1,601 cm^{-1} (C=C, α-β unsaturated ketone), 1,383 cm^{-1} (S=O, sulfate/sulfonyl chloride)	12.56 nm and poly-dispersed, spherical shape	Antimicrobial activity	[323]
Ag NPs	*Simpicillium lanosoniveum*	430	Alcohol and phenolic group at 3,330 cm^{-1} (O–H or N–H), carboxylic acids at 2,343 cm^{-1} (O–H), amino acid at 1,643 cm^{-1} (C=O), phenol group at 1,079 cm^{-1} (O–H)	20–25 nm, spherical, polydisperse	Antioxidant, antibacterial, antiangiogenic, and cytotoxic activity	[324]
Ag NPs	*Cleome brachycarpa* aqueous extract	437	3,293 cm^{-1} (O–H, phenol), 1,389 cm^{-1} (C–N, amide group), 1,189 cm^{-1} (phenol)	20–80 nm, spherical	Anticancer activity	[325]
Ag NPs	*Rhizoctonia solani* fungi extract	420	3,609 cm^{-1} (O–H, phenolic group), 2,878 cm^{-1} (–C–H), 2,141 cm^{-1} (C–N group), 1845 cm^{-1}, 1,321 cm^{-1}, and 801 cm^{-1} (C–O–, –C–O–C–, amide, and N–H)	5–10 nm, face centered cubic shape	Antimicrobial activity	[326]
Ag and CuO NPs	*Amomum subulatum* fruit extract	245 and 440	3,321 cm^{-1} (O–H, N–H), 1636 cm^{-1} (C=C–) and 3,323 cm^{-1} (N–H), 1638 cm^{-1} (–C=C–), 1,364 cm^{-1}, (C–N), 1,145 cm^{-1}, (C–O–C)	20.6 nm and 24.7 nm spherical, polydisperse	Antibacterial, anticancer activity	[42]
Ni NPs	*Alhagi maurorum* leaf aqueous extract	341	414, 474 and 617 cm^{-1} (Ni–O), 404, 2,927 cm^{-1} (O–H) and (C–H), 1,431–1,675 cm^{-1} (C=C) and (C=O), 1,261 cm^{-1} and 1,085 cm^{-1} (–C–O), (C–N)	20.56–36.63 nm, spherical shape	Anticancer activity	[327]
Ni NPs	*Fumaria officinalis* leaves extract	341	433, 534, and 603 cm^{-1} (Ni–O), 3,404 cm^{-1} and 2,927 cm^{-1} (O–H) and (C–H), 1,431–1,675 cm^{-1} (C=C and C=O), 1,261 cm^{-1}, 1,085 cm^{-1}, (C–O, C–N), 1,675 cm^{-1} (C=C and C=O), 1,261 cm^{-1}, 1,085 cm^{-1} (–C–O, C–N)	16.85–49.04 nm, spherical shape	Anticancer activity	[328]
CaO NPs	*Ficus carica* fruit extract	360	661 cm^{-1} (Ca-halogen), 767 cm^{-1} (Ca–O), 809 cm^{-1} (C–H), 897 cm^{-1}, (C–C–, Ca–O–Ca), 954 cm^{-1} (OH, alcohol), 1,195 cm^{-1} (amine), 1,503 cm^{-1}, 2,574 cm^{-1} (COOH), 2,945 cm^{-1} (C–H), 3,386 cm^{-1} (N–H–, C–H–, O–H) 3,696 cm^{-1} (amide)	68.6 nm, irregular shape	Antibacterial, antibiofilm activity	[329]

Table 4: Continued.

Type of NPs	Plant extract used	UV–visible (nm)	FTIR	Size/shape/morphology	Biological activity	References
CeO_2 NPs	*Colocasia esculenta* leaf extract	213	3,431 cm^{-1} (O–H), 1,077 cm^{-1} (C–O), and 1,634 cm^{-1} (C=O, carboxylic acids and esters)	2.04 nm, spherical	Seed germination	[330]
CeO_2 NPs and CuO NPs	Fenugreek leaves aqueous extract	200–900	NA	7.2 nm and 10.96 nm, spherical	Anticancer activity	[331]
CuO NPs	*Ganoderma sessile* fungus extract	290.73	3,387 cm^{-1} (N–H), 3,268 cm^{-1} (OH), 1,077 cm^{-1} (R-NH_2)	1–15 nm (mean size 4.5 ± 1.9 nm), quasi-spherical	Antibacterial, anticancer activity	[332]
CuO NPs	*Aloe vera* leaves extract	288	NA	27.35, 20.79, and 22.18 nm (at different concentration), spherical	Antibacterial, anticancer activity	[333]
CuO NPs	*Phyllanthus reticulatus/Conyza bonariensis* leaves extract	375	589 cm^{-1} and 616 cm^{-1} (Cu–O), 1,609 cm^{-1}, 3,200–3,500 cm^{-1} (H–O–H) and (O–H)	4–14 nm homogenized, monodisperse nanospheres.	Antibacterial, antioxidant activity	[334]
FeO NPs	*Leptolyngbya* sp. L-extract	300	3,272 cm^{-1} (O–H), 1,650 cm^{-1} (amino group), 2,990 cm^{-1} (methylene group)	23 nm, crystalline rhombohedral hematite	Antibacterial, antifungal, antioxidant activity	[335]

wavelength than light. They are produced when electrically charged particles decelerate [349]. While the peak intensity reveals the location of atoms and the electron density inside the unit cell, the peak positions reveal the particles' translational symmetry form and size [350]. Because the XRD peaks produced are excessively broad, this approach is inappropriate for use with amorphous materials and particles smaller than 3 nm. Scherrer's equation is used to calculate crystal size [351].

9.4. Dynamic Light Scattering. DLS is also referred to as QELS or photon correlation spectroscopy. DLS is a technique used to determine the size and distribution of hydrodynamic particles of various sizes [352]. DLS is currently one of the quickest and most popular methods for determining particle size in the range of 1 nm to 1 m [353, 354]. It is also cost-effective and time-saving because it is a rapid analyzer. The DLS technique is used to determine changes in the intensity of scattered light caused by Brownian motion in a suspension or solution. Brownian motion is the random movement of particles from any direction in a zigzag pattern. Larger particles move slower, cover a shorter distance, and scatter more light than smaller particles, according to Brownian motion analysis. The hydrodynamic diameters are influenced by the size and shape of the macromolecules [355, 356]. Because larger particles scatter more light than smaller particles, even small amounts of aggregates or dust particles can cause the particle size distribution to shift to a larger value. A typical DLS consists of a computer, a digital signal processor correlator, a laser, and a detector. The sample in the cell in the DLS instrument is illuminated by the laser that is emitted by the laser light source. Then, one of two detectors one at a 90° and one at a 173° scattering angle is used to capture the dispersed light signal. Greater flexibility in terms of choosing measurement circumstances is made possible by the existence of two detectors. The refractive index and viscosity of the liquid are the only factors needed to interpret the measurement result because particles can be dispersed in a wide range of liquids. A graph is produced due to the obtained optical signal changing due to the particles' relative positions shifting randomly [357, 358].

9.5. Transmission Electron Microscop. A TEM was used to record the morphology of the NPs because TEM is based on the electron transmittance principle, it can provide information about the bulk material at magnifications ranging from very low to very high. TEM also provides critical information about two or more entities [359]. An electron beam is passed through an ultra-thin section of the microscopic object. After interacting with the sample, the electron beam transforms into unscattered, in-elastically scattered, or elastically scattered electrons. The scattered or unscattered electrons are then focused and projected on the screen by a series of electromagnetic lenses. This results in an amplitude-contrast image, a phase-contrast image, electron diffraction, or a shadow image with varying darkness based on the density of unscattered electrons [360]. TEM provides quantitative chemical information about particles, as well as size distribution and high-resolution images. Magnification is defined as the ratio of the distance between the objective lens and the specimen and the distance between the objective lens and its image plane [361]. The resolution and magnification of TEM are higher than those of SEM. TEM can also be used to visualize the role of capping agents and metabolite encapsulation of Ag NPs [362]. One of the disadvantages of TEM is the requirement for a large sample section and a high vacuum.

9.6. Brunau–Emmet–Teller. The application of the BET characterization approach takes center stage as a revolutionary force in the research of green NPs. As society shifts toward more sustainable actions, the synthesis of nanomaterials using ecologically acceptable methods has become a focus point. BET emerges as a strong tool for revealing the complicated surface features of these environment-friendly NPs [363]. Based on gas adsorption principles, BET examines the specific surface area, pore structure, and texture of materials, providing insights critical for optimizing the performance of green NPs across varied applications. The synthesis of these NPs using green methods, such as plant extracts or microbes, not only emphasizes ecological responsibility but also lays the foundations for BET to carefully investigate their nanoscale properties, elucidating their potential in catalysis, sensing, and environmental remediation. Various reports suggested BET technique to determine the surface area of synthesized green NPs. One report stated that cuboidal shaped α-Fe_2O_3 NPs were synthesized by utilizing leaf extract of *Tabebuia aurea* showed greater surface area, i.e., 31.03 m^2/g in comparison to the commercially synthesized α-Fe_2O_3 NPs, and pores found mesoporous [364]. Green NPs synthesized by employing biological techniques represent an evolution in the search for environmentally friendly nanomaterials. With its ability to quantify the surface area available for gas adsorption, BET becomes a beacon guiding researchers through the nanoscale complexity of these environmentally benign particles. By submitting the NPs to gas adsorption–desorption cycles, BET determines their specific surface area, revealing the porous topography that often dictates their catalytic activity and reactivity. This is especially relevant in the context of catalysis, where the exposed surface area of nanoparticles is a vital parameter controlling their efficacy as a versatile characterization technique, BET not only quantifies this critical parameter but also investigates the pore size distribution, offering a thorough understanding of the nanoscale architecture that influences the catalytic behavior of green NPs.

9.7. Atomic Force Microscopy. AFM is a type of scanning probe microscopy used for high-resolution imaging and structural characterization of nanoscale surfaces. It is utilized to examine the size, shape, and outer area of synthesized NPs. It is for functional imaging and manipulation of biomolecules at all levels of an organization has enabled significant progress in structural biology over the last few decades and has led to the discovery of novel structural components of biological significance across many disciplines including biomedicine, biochemistry, biophysics, and cell biology. [365]. AFM can provide high-resolution topographic images covering the molecular to cellular ranges and explore biophysical and biochemical samples with exceptional temporal resolution. AFM is employed in combination with complementary nanoscopy,

microscopy, and spectroscopy techniques [366]. This technique emerges as a pioneering force in the field of nanotechnology, peeling back the layers of the nanoscale universe, and diving into the complexities of green MNPs. This characterization method, developed in the 1980s by physicists Gerd Binnig and Heinrich Rohrer, has become a vital instrument in nanoscience, giving researchers new insights into the topographical and structural characteristics of nanomaterials at the molecular and atomic levels [367]. The interaction forces between the tip and the sample surface, which include van der Waals forces, electrostatic forces, magnetic forces, and chemical bonding forces, is the principle of AFM. These forces produce a deflection in the cantilever when the tip is moved closer to the sample surface, which is commonly quantified using a laser beam deflection process and measuring the deflection as the difference between the intensity of the beam, recorded by a four-quadrant photo diode. This deflection can be used to adjust the tip's vertical position while maintaining a constant distance between the two [368].

Green NPs are frequently synthesized by using biological methods such as plant extracts and microbes. AFM can provide high-resolution images and full surface data and take the microscopic structure of these green NPs. Based on the interaction of a sharp tip with the sample surface, the approach generates representations that go beyond the limits of standard microscopy. AFM captures not only the size and shape of green NPs but also provides a three-dimensional description of their surface, allowing researchers to determine small changes, irregularities, and even chemical composition with unexpected accuracy [369]. AFM has become an advantageous tool in the characterization of green MNPs designed for therapeutic applications in the biomedical field, where nanoparticles offer enormous potential. AFM structural details provide insights into the interactions of NPs with biological entities, helping in the development of targeted drug delivery systems or agents for imaging [370]. The versatile nature of AFM is further demonstrated while investigating the physical characteristics of mechanical qualities like as elasticity, stiffness, and adhesion. In the case of green NPs, AFM is one of the characterization techniques for determination of geometrical characteristics. Several researchers utilize this characterization technique to determine the size and shape of the NPs synthesized by any one of the methods, viz., physical, chemical, and biological methods. According to the report characterization of Au NPs performed by AFM technique and image of the sample surface spans an $8\,\mu\text{m} \times 8\,\mu\text{m}$ region of interest. AFM data processing analysis enabled the average and root mean square roughness values of the plasmonic, Au nanoscale substrate to be determined as 16 nm (average) and 20 nm (root mean square), respectively. The distribution of profile heights shows that particle size ranges throughout a 100 nm region, with a mean value of 50 nm, which is consistent with SEM data [371]. Another study stated Ag NPs synthesized by two different methods further characterized by AFM and DLS techniques. The formed one Ag NPs with a wide size distribution, up to one micron. And the other one has a diameter of roughly 60 nm, as demonstrated by DLS measurements and validated by AFM measurements, which is comparable with previous results for similar reductions [372].

10. Applications of Plant-Mediated Green NPs

Currently, MNPs, MONPs, and BMNPs are used in numerous fields of science. In the past few years, NPs have frequently been reported to play an important role as biosensors in health care and agriculture development, as shown in Figure 9 [373]. In several other fields such as in food industries and construction units, MNPs are used extensively. They have been examined for a variety of clinical uses, including imaging contrast agents, tumor-targeting genes, and drug carriers [374, 375].

10.1. Biomedical Application of Green MNPs, MONPs, and BMNPs. Over the past 10 years, medications made with nanotechnology have received a lot of interest. NPs with special characteristics, such as their tiny size and propensity to pass through delicate blood arteries, junctions, and barriers, have made this field one of the most extensively examined and investigated. They offer significant benefits in terms of enhancing medication bioavailability, solubility, toxicity protection, pharmacological activity, distribution, and prevention of chemical and physical degradation as well as enhanced drug stability inside the body [376]. Nanomedicines have demonstrated a greater ability to bond with biomolecules and a decrease in tissue oxidative stress and inflammation. Over the years, thousands of unique nanomedicines have been developed; they have a variety of uses in many sorts of ailments. Inorganic NPs are among them, as FeO magnetic NPs have various applications in the anticancer technique known as hyperthermia; they generate heat and damage tissues nearby. FeO NPs exhibit a variety of features, including good solubility, stability, dispersion, biocompatibility, and a long circulation duration [377].

10.1.1. Analgesic Activity of Green Ag NPs. Green synthesized Ag NPs frequently contain bioactive substances such as flavonoids and polyphenols derived from the plant extracts utilized in their synthesis. These substances reduce inflammation by blocking proinflammatory mediators and enzymes, such as COX and LOX [378]. Inflammation is a significant source of pain, and Ag NPs can reduce pain associated with inflammatory diseases by lowering inflammation. Some research suggests that Ag NPs can interact with brain receptors and pain transmission pathways [379]. These interactions can cause pain signals to be modulated, resulting in decreased pain perception. The actual processes of this brain modulation are currently being researched. Another interesting feature is the possible synergy between Ag NPs and the natural plant chemicals employed in their manufacture. Many green methods make use of plant extracts high in bioactive chemicals, which may increase Ag NPs analgesic activities. When compared to standard analgesic medicines, these synergistic effects can lead to better pain management and fewer side effects. Leaf extract of *Rosa damascena* was employed to reduce silver nitrate and help in the production of Ag NPs that were evaluated for analgesic activity against the Wistar rat model [380]. *Coriandrum*

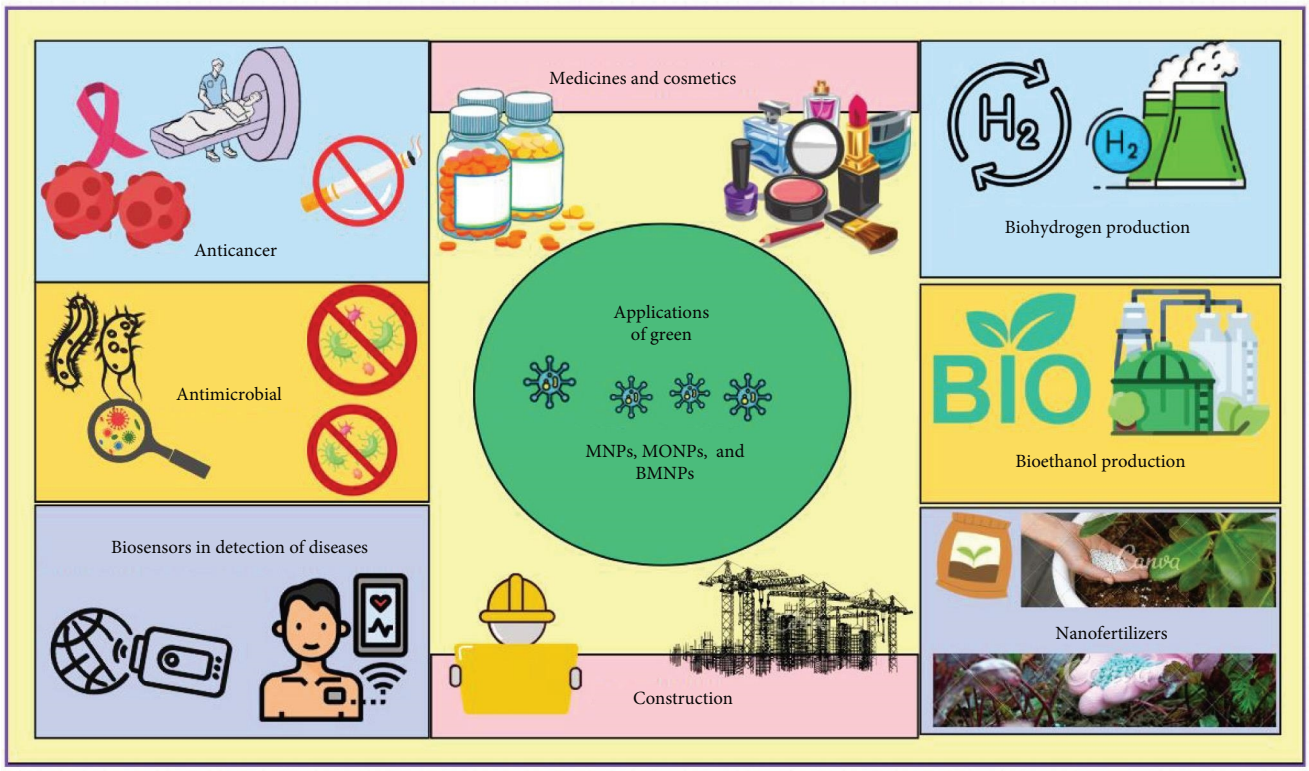

Figure 9: Significant applications of plant-mediated green MNPs, MONPs, and BMNPs.

sativum L. leaf extract was utilized to produce Ag NPs, which demonstrated superior antianalgesic action after carrageenan injection compared to piroxicam (6.0 mm), plant extract (8.25 mm), and Ag NPs (7.32 mm) (231). Accordingly, the analgesic action of green-synthesized Ag NPs offers the way for safer and more effective analgesic treatments, addressing the complexities of pain and increasing the quality of life for countless people.

10.1.2. Antiviral Activity of Green Ag NPs. In vitro investigations on the antiviral activity of Ag NPs have yielded promising findings against a wide range of viruses. The effect of Ag NPs on respiratory syncytial virus, a common respiratory virus, was studied, and it was discovered that they reduced viral multiplication in vitro, indicating their potential utility against respiratory viral infections [381]. The potential action of green Ag NPs against HIV was tested using *Centella asiatica* leaf, stolon, and root extract. They discovered that Ag NPs could limit the replication of HIV-1, the virus that causes AIDS, in human T-cells. The NPs seemed to be focused on the viral protease enzyme, which is required for viral maturation [382]. Another study found that Ag NPs have antiviral properties against HSV-1 and HSV-2, which cause oral and genital herpes. Ag NPs significantly inhibited HSV attachment and penetration into host cells [383, 384]. Ag NPs antiviral activity has been investigated against coronaviruses, notably SARS-CoV-2, the virus responsible for COVID-19 [385, 386]. In vitro investigations have revealed that Ag NPs can suppress viral replication and diminish coronavirus infectivity. The antiviral activity of Ag NPs against bacteriophages, viruses that infect bacteria, has also been studied [387]. Green Ag NPs synthesized from clove buds stated antiviral activity in vitro and in vivo [388]. Studies have shown that Ag NPs can successfully inhibit bacteriophage replication in vitro. Antiviral activity involves several pathways, including viral replication disruption, viral entrance inhibition, viral enzyme inhibition, development of oxidative stress, improved immunological response, and anti-inflammatory effects. Ag NPs have been demonstrated to interfere with different phases of viral replication within host cells, including transcription, translation, and RNA/DNA replication. This interference inhibits viral replication and viral particle formation. By interfering with viral glycoproteins and blocking them from attaching to cellular receptors, Ag NPs can disrupt viral attachment and entrance into host cells. This first disturbance makes viral infection more difficult [389]. Ag NPs can directly interact with viral replication enzymes such as proteases and polymerases. These enzymes are inhibited, which disrupts viral replication and assembly. When Ag NPs come into contact with viruses, they cause oxidative stress within the infected cells, destroying viral proteins and genetic material and ultimately blocking viral reproduction. Ag NPs increase the synthesis of immunological components such as interferons and cytokines, both of which are important in antiviral defence. Ag NPs have anti-inflammatory capabilities that can reduce the excessive inflammation that is frequently linked with viral infections. This helps to reduce the adverse effects of inflammation during the infection [390].

10.1.3. Anticoagulant Activity of Green Ag NPs. The manufacture of Ag NPs utilizing plant extracts to create an

anticoagulant effect is a growing topic of interest in both nanotechnology and medical research. Ag NPs are well-known for their amazing features, including their capacity to suppress blood clotting, making them prospective candidates for anticoagulant treatments [391, 392]. Several plant extracts have been examined for their role in Ag NPs formation as well as their capacity to improve the anticoagulant properties of these NPs [393]. *Selaginella bryopteris* is a plant extract that is extensively utilized in the synthesis of Ag NPs. This plant includes a variety of bioactive chemicals, including polysaccharides and phenolic compounds, which can act as reducing and stabilizing agents in the synthesis of Ag NPs. The synthesized Ag NPs were found to be nontoxic because they did not hydrolyze red blood cells, cause oedema or bleeding in experimental animals, and possess anticoagulant and antiplatelet properties. As a result, the author proposed that it would be a better option in the biomedical sector, particularly for treating thrombotic diseases [394]. Several other plant extracts (seeds) have been reported to synthesize Ag NPs with anticoagulant action, including *Synsepalum dulcificum*, *Theobroma cacao*, *Cola nitida*, and *C. nitida cola* [395].

10.1.4. Biofilm Inhibitory Activity of Green Ag NPs. Biofilm inhibition is an important part of treating bacterial infections and preserving hygiene in a variety of fields, including healthcare and food processing. Green Ag NPs have emerged as a useful agent for reducing biofilm development due to their unique antibacterial characteristics and ecologically friendly manufacturing technique. The term "green" refers to the environmentally benign and sustainable technique of synthesizing Ag NPs, which frequently involves plant extracts or other natural sources. These NPs have attracted attention for their capacity to disrupt the formation and stability of biofilms, which are complex communities of bacteria embedded in an extracellular matrix [396]. Green Ag NPs have been found to suppress biofilm formation in several ways. First, they can directly interfere with bacterial adhesion to surfaces, preventing early attachment and colonization. This interference is related to Ag NPs capacity to break the biofilm matrix and prevent the formation of extracellular polymeric substances, which are essential for biofilm structure and stability [397]. Furthermore, Ag NPs have antibacterial properties because they release Ag ions, which can infiltrate bacterial cells, disturb biological processes, and ultimately lead to cell death. Because of this dual activity, green Ag NPs are efficient at inhibiting both early-stage biofilm development and matured biofilms [398]. The leaf extract of *Encephalartos laurentianus* was utilized to synthesize Ag NPs. The researcher discovered a significant inhibitory effect against *C. albicans* [399]. Another study found that Ag NPs synthesized from *Piper betel* have strong antibiofilm activity against *C. violaceum* (which causes bacterial illness) [400]. Another study revealed that combining antibiotics with biogenic Ag NPs could be utilized to treat bacterial infections. Researchers synthesized Ag NPs from *Allophylus cobbe* leaf extract and discovered antibacterial and anti-biofilm properties against a variety of human pathogenic bacteria [401]. In conclusion, the biofilm inhibiting ability of green Ag NPs represents a promising route in the ongoing war against bacterial diseases, providing both effective antimicrobial action and an environmentally benign way to NPs synthesis.

10.1.5. Anticancer Activity of Green Ag NPs, Au NPs. Au is also an excellent choice for NPs synthesis due to its great dispersion, tiny size, and vast surface area. Au NPs have recently been shown to be more effective in drug administration because of their self-assembled nature [376, 402]. Au NPs cause oxidative stress and have anticancer effects by taking up incident photons and transforming them into heat that kills malignant cells. At some doses, cationic Au NPs (2 nm in diameter) are hazardous. Smaller Au NPs showed a lower protein-to-protein ratio than bigger ones [403]. According to the literature, when Au NPs were exposed to Hela (cervical) tumor, ROS increased which may lead to the oxidation of lipids, proteins, and other molecules in cervical cancer cells [404]. Au has great resistance to oxidation by moisture, oxygen, and acids, as well as its biocompatible nature, it has received interest in the biomedical sector, notably in cell targeting, tumor detection, drug administration, and cancer therapy [405]. Biosynthesized Au NPs with spherical shapes and average diameters of 95 nm inhibited the proliferation of MCF-7 (breast) cancer cells by controlling the expression of pro- and anti-apoptotic proteins (p53 and Bcl-2) with an IC_{50} value of 4.76 μg/ml [406, 407]. Another study reported that A549 (lung) cancer cell lines were inhibited by spherical-shaped biosynthesized Au NPs. These Au NPs, which ranged in size from 80 to 120 nm, were lethal to malignant cell types by upregulating several proinflammatory genes such as tumor necrosis factor-alpha, interleukin-10, and IL-6, among others [408].

Ag NPs are suitable due to their unique catalytic activity, stability, and medicinal value such as their antiviral, antibacterial, and antifungal properties. They also possess antiproliferative properties and the capacity to trigger cell death, hence, can be employed as anticancer drugs [409]. As revealed by literature spherically shaped biosynthesized Ag NPs with diameters ranging from 7.39 to 80 nm showed inhibitory effects against cancer cell lines HCT 15, HT29 cells, and HCT-116, with IC_{50} values ranging from 5.5 to 100 μg/ml [410, 411]. Another study reported the inhibition of A549 (lung) cancer cell line by biosynthesized Ag NPs has been effective. The produced NPs were spherical with diameters ranging from 13 to 136 nm and showed dose-dependent inhibitory activity with varying IC_{50} and LD_{50} values [412, 413]. Some other spherical-shaped Ag NPs inhibited the Hep-G2 (liver) cancer cell lines [414, 415]. Plant-mediated Ag NPs and Au NPs were explored to combat leukaemia, for this several plants were reported in the literature such as *A. indica*, *H. sabdariffa*, *C. sinensis*, *Boswellia serrata*, *Lens culinaris*, *Thymus vulgaris*, *C. sativa*, *Verbena officinalis*, *T. vulgaris*, *B. serrata*, *Abelmoschus esculentus L.*, *Dracocephalum kotschyi*, and *Sargassum glaucescens*, respectively [416].

10.1.6. Anticancer Activity of Green ZnO NPs, CuO NPs. Due to their wide biological activity, ZnO NPs have caught the attention of researchers from all over the world. They can significantly increase pharmacophore bioactivity while being

less toxic and biodegradable [417]. Upon 150 min of exposure, green synthesized ZnO NPs showed the maximum scolicidal action at 400 ppm concentration, with a 100% fatality rate. The treated protoscolices lost viability and underwent morphological changes [418]. ZnO nanoflowers were created using hydrothermal and precipitation processes and their antibacterial activity and photo-catalytic activity were compared [419]. Thirty-two nanometers size ZnO NPs were synthesized using *Origanum majorana* leaf extract. Furthermore, the antioxidant and anticancer potential of the ZnO NPs was examined. The antioxidant activity of spherical NPs was substantial. When compared to the normal cell line, the cytotoxicity indicated IC_{50} values of 16.8 6.7, 194.3 5.84, and 33.5 μg/ml after 48 hr treatment in both MCF7 (breast) and HT-29 (colon) cancer cells [420]. Another study revealed that *C. papaya* leaf extract was used to synthesize ZnO NPs and their effect was investigated on seed germination, root length, shoot length, and antioxidant activity at different concentrations (25%, 50%, 75%, and 100%) [421]. The potent anticancer action was demonstrated by CuO NPs made from aqueous leaf extract against the breast cancer (AMJ-13) cell line and the ovarian (SKOV- 3) cancer cell line, with IC_{50} values of 1.47 and 2.27 g/ml, respectively [422]. CuO NPs produced by plants that were spherical, hexagonal, and 26.6 nm in size had inhibitory effects on cervical cancer cell lines by activating ROS-mediated apoptotic pathways in HeLa [422]. Biosynthesized spherically shaped CuO NPs of 26–30 nm diameters with a 56.16 g/ml IC_{50} were used to inhibit MCF-7 breast cancer cell lines [423]. Similarly, spherically formed CuO NPs of 12 nm size produced from aqueous leaf extracts of several plants showed cytotoxicity against HeLa, MCF-7, and A549 cancer cell lines, with IC_{50} values varying depending on the plants, utilized [424, 425].

10.2. Plant-Mediated Green NPs Used in Biosensors for Disease Detection. Nano-biosensors are sophisticated instruments that detect a wide range of chemicals at low concentrations with great specificity. The ability to screen for early disease has recently been made possible by the discovery of multiple biomarkers for various distinct physiological states. Biomarkers are the body's early warning systems; they are biological status indicators that offer a standardized and accurate technique to gauge the development of disease or infection [426]. Biosensors are made up by incorporating biological components and nanoscale materials. The detection specificity is greatly boosted by using chemically inert and biocompatible nanomaterials for biomedical techniques since many microbes, viruses, bacteria, and pathogens have dimensions that are similar to those of nanostructures. Biosensors based on nanomaterials have also been used to detect and measure a variety of environmental contaminants and harmful compounds in food [427]. Several types of biosensors are now available for diagnostic purposes some are enzymatic electrochemical biosensors, nonenzymatic electrochemical biosensors, aptasensors, electrochemical immunosensors based on metals, DNA-based metal nano-biosensors, and electrochemical cytosensors [428]. As developments are raised in molecular biology, researchers can now determine how diseases are triggered by specific molecules involved in transcription and translation. Many scientists determined cancer biomarkers by using Au NPs as biosensors. In ovarian cancer and breast cancer, BRCA1 mutation is the most prevalent oncogenes. A DNA capture probe immobilized in Au NPs was reported to be capable of detecting these newly discovered prognostic indicators, with detection accuracy reaching femtomolar levels [429]. An electrochemical approach to treating prostate cancer-specific DNA sequences (PCA3) utilizing chondroitin sulfate Au NPs has been demonstrated [430]. Another scientist reported the use of biosensors in the detection of nucleic acid in viruses [431]. Transition metal oxides such as NiO, MgO, and CoO have been widely used as biosensor components due to their quick and reversible Faradic redox reactions at the electrode–electrolyte interface such as bioelectrode made of NiO was employed to detect the influenza virus [432]. Some other plant-mediated green NPs that are used in the development of biosensors are Au, Ag, and Pt which help in nucleic acid detection [433].

10.2.1. Plant-Mediated Green NPs Used in Biosensors for Agriculture Development. MNPs produced by green synthesis offer a wide range of potential uses in agriculture to boost crop yield. Due to the lack of pollution and cost-competitiveness with fossil fuels, biofuels are quickly becoming viable alternatives to traditional sources of renewable energy. Researchers investigated the use of NPs in biofuel processes such as biohydrogen, biogas, biodiesel, and bioethanol synthesis to improve process yields. Various forms of nanomaterials like metallic nanotubes and nanofibers are employed in these bioprocesses [434]. Due to their capacity to immediately identify infections as well as their robust monitoring and analytical capabilities, biosensors have changed agricultural systems to boost the production of quality agricultural products. Nanobiosensors are a type of biosensor that has been developed to function as an analytical unit by combining a biologically sensitive element with a physicochemical transducer [435]. Different types of nanobiosensors, such as enzymatic biosensors, genosensors, aptasensors, and immunosensors, are built with a variety of electrochemical, biological, or physicochemical transducers. Because of their rapid, specific, and selective efficacy in detecting poisons and plant diseases, these sensors have garnered a lot of attention [436].

10.3. Plant-Mediated Green NPs as Nanofertilizers. Nanofertilizers are macro- or micro-nutrient fertilizers with particle sizes smaller than 100 nm that are used to boost crop production. Bulk materials larger than 100 nm in size that have been treated with nanoscale structures, such as bulk fertilizers covered with NPs, have also been referred to as nanofertilizers [437, 438]. Nanofertilizers are considered essential to precision farming because they supply nutrients in a regulated and site-specific manner, enhancing nutrient usage efficiency and lowering waste. Nanofertilizers are NPs that are used to stimulate crop growth. The use of MNPs, MONPs, and BMNPs has been tested and confirmed to boost crop growth and quality [439, 440]. Several types of NPs can also be used in seedlings to prevent viral infection. In vitro culture is one of the most effective methods for viral elimination

in seedlings [441]. The use of green NPs as chemicals to regulate the virus might be an alternative to antiviral medications. MNPs, BMNPs, and MONPs, on the other hand, have been shown in studies to have stronger antiviral efficacy when used in cultures before infection [442, 443]. Fe, Zn, and TiO_2 are common trace metallic NPs found in nanofertilizers [444, 445]. Studies have shown that these NPs may penetrate the plant and improve water and nutrient uptake as well as absorption. It has been shown that NPs can increase enzyme activity, seed germination, and plant development [446]. To reduce dependency on chemical fertilizers for sustainable agricultural development and food security as well as to meet the nutritional demands of the world's rapidly expanding population, the use of ZnO NPs in agriculture is emerging as a viable tool for plant science [447, 448]. ZnO NPs are being studied in agriculture to achieve sustainable development and to examine their potential to promote growth by studying them as nano-fertilizers in crops such as corn, onion, tomato, pepper, and wheat [449].

10.4. Plant-Mediated Green NPs Used in Dark Fermentative Biohydrogen Production. Scientists evaluated the influence of Cu and $CuSO_4$ NPs on biohydrogen generation by utilizing *C. acetobutylicum* and *E. cloacae*. The inclusion of Cu and $CuSO_4$ NPs was shown to have a detrimental effect on the formation of volatile fatty acids, resulting in the suppression of acetate and butyrate biohydrogen producing pathways [450, 451]. The study revealed that Fe NPs increased biohydrogen output significantly when compared to the control trial. This resulted in a higher biohydrogen output of 1.9 mol H_2/mol glucose at a concentration of Fe of 100 mg/l. The NPs increased glucose consumption twofold. These findings are consistent with previous research since iron is a major component of ferredoxin and also serves as an electron carrier in hydrogenase enzymes [451].

10.5. Plant-Mediated Green NPs Used in Food and Bioethanol Production. The incorporation of nanotechnology results in improvements in food production, processing, protection, and packaging, for example, a nanocomposite. Production of bioethanol with the help of nanotechnology has become very economical and has many environmental benefits. It is one of the most widely utilized renewable fuels in the automobile sector. Bioethanol offers several advantages, including a wide spectrum of flammability for combustion, a high evaporation enthalpy, and a high-octane number [452]. Sugarcane, rice, sorghum, barley, wheat, oats, and corn are currently utilized to produce the majority of the world's bioethanol [453]. The researcher mounted galactosidase on SiO_2 nanoparticles for whey hydrolysis, together with *S. cerevisiae* and *K. marxianus* cultures. This experimental approach produced a significant bioethanol output of 63.9 g/l with a production efficiency of 42.6% [454].

10.6. Plant-Mediated Green NPs Used in the Construction Field. Nanotechnology has been widely used for construction purposes as it reduced the cost and increased the safety of building operations. For example, when nanosilica (SiO_2) is added to regular concrete, the NPs can increase their mechanical qualities as well as their durability [455]. The inclusion of haematite (Fe_2O_3) NPs in the concrete boosts its strength. Steel is the most common and commonly utilized material in the building sector. Steel qualities may be increased by applying nanotechnology in steel. For example, in bridge building, the use of nanosize steel provides stronger steel cables [456]. The use of nanotechnology improves the blocking of light and heat passing through the windows. Paints with self-healing properties, corrosion resistance, and insulation are created by incorporating NPs into the paint. Because these paints' hydrophobic properties repel water, they can be used to coat metal pipes to protect them against saltwater assault. The addition of NPs to paints improves their performance by making them lighter with improved properties, so when used on aircraft, for example, it may reduce their overall weight and the amount of paint required, which is beneficial to the environment as well as the company in terms of cost savings [457].

11. Disadvantages of Green NPs for Humans

Green metallic-based NPs, which are synthesized using environmentally friendly or "green" methods, have advantages in terms of sustainability, but they also have some drawbacks for human health, including toxicity, bioaccumulation, immune system activation, oxidative stress, environmental concerns, regulatory challenges, and uncertainty about long-term health effects. Ag NPs are frequently synthesized by utilizing environmentally friendly processes and employed in a variety of applications, including wound dressings [297] and antibacterial coatings [298]. Ag NPs, on the other hand, can be harmful to human cells. When these NPs come into touch with the skin or mucous membranes, they can induce irritation, allergic responses, or even more serious toxicity if they are absorbed into the bloodstream [299]. Green Au NPs have been exploited in medication delivery and imaging applications [458]. These NPs are small enough to be absorbed by cells and tissues, and they can accumulate over time. Long-term AuNPs exposure may result in bioaccumulation in essential organs, potentially causing organ damage or dysfunction [459]. Green synthesized CuO NPs with antibacterial characteristics [460] can activate immune responses and cause inflammation when they interact with the immune system [461]. Chronic inflammation has been linked to a variety of health problems, including autoimmune illnesses [462]. Green-mediated TiO_2 NPs are widely used in sunscreens and cosmetics due to their UV-blocking properties [463]; however, when these NPs are exposed to sunlight, they can generate ROS, producing oxidative stress on the skin. This oxidative stress can accelerate skin aging and increase the risk of skin cancer [464]. The regulatory environment for NPs, particularly green synthesized MNPs, is still changing. Difficulties in formulating safety standards and guidelines might lead to uncertainty about their safe application. This can make it challenging to protect human health during manufacture, use, and disposal. Plant-mediated FeO NPs have shown promise in magnetic resonance imaging and medication delivery [465]. While they are widely regarded as safe, the long-term health implications of regular exposure to these NPs, particularly in industrial contexts, are not well-understood [466]. Green Cu NPs can reduce the environmental

impact of manufacturing; however, the release of these nanoparticles into the environment is still possible. Cu is harmful to aquatic life, and its presence in water bodies can impair aquatic ecosystems [467]. Humans can be affected indirectly by contaminated water sources or by eating afflicted aquatic species. These are significant disadvantages, hence extensive research, risk assessment, and regulatory control are required to mitigate these dangers and ensure the safe use of these NPs.

12. Conclusion and Future Prospectives

This study concentrated on nontoxic, cost-effective, and environmentally friendly plant-mediated green synthesis of MNPs, MONPs, and BMNPs rather than physiochemical techniques. The plant-mediated green NPs have emerged as remarkable entities with diverse applications across various industries, such as biomedical, agriculture, biosensors, food processing, construction, energy, and the environment. This review has summarized information about the antibacterial and anticancer potential of plant-mediated green MNPs, MONPs, and BMNPs (Ag, Au, Co, Cu, Fe, Zr, Bi_2O_3, CeO_2, Co_3O_4, $CoFe_2O_4$, CuO, Fe_2O_3, NiO, TiO_2, ZnO, ZrO_2, Ag-Au, Ag-Cr, Ag-Cu, Ag-Zn, Ag-CeO_2, Ag-CuO, Ag-SeO_2, Ag-TiO_2, Ag-ZnO, Cu-Ag, Cu-Mg, Cu-Ni, Pd-Pt, Pt-Ag, ZnO-CuO, ZnO-SeO, ZnO-Se, Se-Zr, Co-Bi_2O_3). Moreover, it imparts knowledge about antibacterial and anticancer mechanisms, several characterization techniques, and versatile applications. In green synthesis approach, different parts of plant extracts were utilized which shows remarkable antibacterial and anticancer potential against the tested microbial species and targeted cancer cells respectively. This study's findings point the way forward for further research on green NPs development in the environmental and biomedical sectors. The use of green-synthesized NPs holds great promise in biomedical applications such as drug delivery systems, imaging agents, and targeted therapies. Further research and validation will lead to the development of more efficient and biocompatible nanomedicine approaches. To fully unlock the potential of green nanotechnology, further research and data validation are imperative. It is crucial to understand the mechanisms governing the release of NPs in these synthesis methods and ensure their long-term stability and safety. Continued collaboration between researchers, industry experts, and regulatory bodies will foster responsible development and facilitate the integration of green nanotechnology into our everyday lives, ushering in a future that is sustainable, technologically advanced, and environmentally conscious.

Abbreviations

Bacterial Species

A. alternate:	*Alternaria alternate*
A. stephensi:	*Anopheles stephensi*
A. subpictus:	*Anopheles subpictus*
A. brasiliensis:	*Aspergillus brasiliensis*
A. flavus:	*Aspergillus flavus*
A. niger:	*Aspergillus Niger*
B. cereus:	*Bacillus cereus*
B. foraminis:	*Bacillus foraminis*
B. halodurans:	*Bacillus halodurans*
B. subtilis:	*Bacillus subtilis*
B. annulatus:	*Boophilus annulatus*
C. albicans:	*Candida albicans*
C. glabrata:	*Candida glabrata*
C. krusei:	*Candida krusei*
C. Parapsilosis:	*Candida parapsilosis*
C. tropicales:	*Candida tropicales*
C. cornuta:	*Cassis cornuta*
C. violaceum:	*Chromobacterium violaceum*
C. acetobutylicum:	*Clostridium acetobutylicum*
C. quinquefasciatus:	*Culex quinquefasciatus*
Cryptococcus sp.:	*Cryptococcus species.*
E. cloacae:	*Enterobacter cloacae*
E. faecalis:	*Enterococcus faecalis*
E. coli:	*Escherichia coli*
F. gramium:	*Fusarium gramium*
F. oxysporum:	*Fusarium oxysporum*
H. suis:	*Helicobacter suis*
H. bizzozeronii:	*Helicobacter bizzozeronii*
K. oxytoca:	*Klebsiella oxytoca*
K. pneumoniae:	*Klebsiella pneumoniae*
K. marxianus:	*Kluyveromyces marxianus*
L. acidophilus:	*Lactobacillus acidophilus*
L. innocua:	*Listeria innocua*
L. tropica:	*Leishmania tropica*
M. luteus:	*Micrococcus luteus*
P. vulgaris:	*Proteus vulgaris*
P. aeruginosa:	*Pseudomonas aeruginosa*
S. cerevisiae:	Saccharomyces cerevisiae
S. Albany:	*Salmonella Albany*
S. Typhi:	*Salmonella typhi*
S. enterica/:	*Salmonella enterica/*
S. enteritidis:	*Salmonella enteritidis*
S. Paratyphi:	*Salmonella Paratyphi*
S. typhimurium:	*Salmonella typhimurium*
S. marcescens:	*Serratia marcescens*
S. flexneri:	*Shigella flexneri*
S. albus:	*Staphylococcus albus*
S. aureus:	*Staphylococcus aureus*
S. epidermidis:	*Staphylococcus epidermidis*
S. mutans:	*Streptococcus mutans*
V. cholerae:	*Vibrio cholerae.*

Bimetallic Nanoparticles

CF:	Cobalt-ferrite
Cu-Ag:	Copper-silver
Fe-Cu:	Iron-copper
Fe-Pd:	Iron-palladium
CFM NPs/$MnCoFe_2O_4$:	Mn-doped cobalt-ferrite nanoparticles
Ag-Cu:	Silver-copper

Ag-Au: Silver-gold
Ti-Ni: Titanium-nickel.

Metals

Cd: Cadmium
Co: Cobalt
Cu : Copper
$CuSO_4$: Copper sulfate
Au: Gold
Fe: Iron
Mg: Magnesium
Ni: Nickel
Pd: Palladium
Pt: Platinum
Se: Selenium
Ag: Silver
Ti: Titanium
Zn: Zinc
Zr: Zirconium.

Metal Oxides

Bi_2O_3: Bismuth oxide
B-TiO_2: Boron-doped titanium dioxide
CeO_2: Cerium oxide
CNTF HNMs: Chitosan-encapsulated-NiO-TiO_2-farnesol hybrid nanomaterials
$CoFe_2O_4$: Cobalt ferrite
Co_3O_4: Cobalt oxide
Co_2O_3: Cobaltic oxide
Co O: Cobaltous oxide
CuO: Copper oxide
rGO: Graphene oxide
In_2O_3: Indium oxide
Fe_2O_3: Iron oxide
Ni-CFO NPs: Nickel (Ni) doped cobalt ferrite (CFO) nanoparticles
NiO: Nickel oxide
SiO_2: Silicon dioxide
TiO_2: Titanium dioxide
ZnO: Zinc oxide.

Nanoparticles

BMNPs: Bimetallic nanoparticles
MNPs: Metal nanoparticles
MONPs: Metal oxide nanoparticles
NC: Nanocomposite
NH: Nanohybrid
NPs: Nanoparticles
NSs: Nanospheres.

Nanoparticles Characterization

AFM: Atomic force microscopy
BET: Brunau–emmet–teller
DLS: Dynamic light scattering
EDS: Energy dispersive
FTIR: Fourier-transform infrared spectroscopy
LSPR: Localized surface plasmon resonance
NTA: Nanoparticle tracking analysis
QELS: Quasi-elastic light scattering
TEM: Transmission electron microscopy
SEM: Scanning electron microscopy
UV: Ultraviolet
Vis: Visible
XRD: X-ray diffraction
ZP: Zeta potential.

Others

DPPH: 1,1-Diphenylpicryl-hydrazyle
AC: Activated carbon
AIDS: Acquired immunodeficiency syndrome
Apaf-1: Apoptotic protease factor-1
COVID-19: COVID-19 disease
CFU: Colony-forming units
COX: Cyclooxygenase
Cyt-c: Cytochrome-c
DNA: Deoxyribose nucleic acid
FADD: Fas-associated protein with death domain
HSV: Herpes simplex virus
HIV: Human immunodeficiency viruses
LPS: Lipopolysaccharide
LOX: Lipoxygenase
MBC: Minimum bactericidal concentration
MIC: Minimum inhibitory concentration
Not available: NA
NADPH: Nicotinamide adenine dinucleotide phosphate
PARP-1: Poly ADP-ribose Polymerase-1
PVA: Polyvinyl alcohol
ROS: Reactive oxygen species
RIP: Receptor-interacting protein-kinase
SARS-CoV-2: Severe acute respiratory syndrome coronavirus 2
SH: Sulfhydryl
UTI: Urinary tract infections.

Data Availability

The supporting literature, data, and other necessary information used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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