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By Green Synthesis Prepared Metal and Metal Oxide Nanoparticles for Medical Application

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Abstract: Nanotechnology, particularly the development of metal and metal oxide nanoparticles, has significantly advanced medical science through improved drug delivery, diagnostic imaging, and therapeutic applications. However, conventional physical and chemical synthesis methods are often costly, energy-intensive, and environmentally hazardous. This review examines green synthesis approaches that utilize plant extracts, microorganisms, and other biological materials as reducing and stabilizing agents for nanoparticle production. Green methods offer enhanced biocompatibility, reduced toxicity, lower production costs, and improved environmental safety compared to traditional techniques. The paper highlights recent progress in green-synthesized nanoparticles—especially zinc oxide and other metal oxides—for antibacterial, anticancer, and biomedical applications. It also discusses key challenges, including process standardization, large-scale production, regulatory concerns, and long-term toxicity assessment. Overall, green nanotechnology represents a sustainable and promising pathway for advancing modern medicine while aligning with principles of green chemistry and global sustainability goals.

Keywords: Principles of Green Chemistry, Nanotechnology, Review of Neonatal

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1. Introduction

Nanotechnology is based on the manipulation of matter at the atomic and molecular level, and it has created a new field of innovation in various scientific areas [1]. This subject is fast changing with the extraordinarily small dimension of the particles, 1-100 times of the size of a particle at least in at least one dimension. These particles are unique in terms of physical and chemical characteristics, unlike the components of blood [2][3].

These distinctive characteristics of nanoparticles make it one of the best available in a broad variety of applications. They are key elements in coming up with better drug delivery systems, enhancing diagnostics tools and providing new treatments in the medical field [2]. These nanomaterials have distinct properties including large surface-to-volume ratios and quantum effects, which brings their application in cancer therapy, infection control, as well as the advanced bioimaging methods [2][4].

More specifically, small metal and metal oxide particles have received significant interest because of their versatile characteristics in optics, magnetism, catalysis, and electricity [2],[5]. These properties differ significantly in terms of size, composition, crystal structure and shape. As the demand of these materials rises in the pharmaceutical sector,

cosmetics, and electronics, there are need to identify sustainable and affordable ways of manufacturing these materials [6].

Green synthesis has become one solution to the challenge of need to substitute the traditional chemical and physical approaches in response to the demand. In this method, emphasis is put on the utilization of natural material including plant extracts and microorganisms to convert the metals into nanoparticles [7][8]. The point of it is that it contributes to the diminution of the environmental and health damage that might occur with the traditional preparation processes [9][8].

The sustainable method will minimize the consumption of harmful chemicals and energy, in line with the principles of green chemistry and to promote the advancement of biocompatible nanoparticles [10][6]. We explore green manufacturing techniques applied to metal and metal oxide nanoparticles in this review and critically examine how they operate, advantages as well as their limitations especially in different medical applications.

We also look at the advancements achieved in the use of these green nanoparticles, diagnostic imaging and drug delivery systems and how they are bound to transform the modern day medicine [11]. Moreover, the use of plants to prepare nanoparticles which exploits the chemical multiplicity of medicinal plants is a green way of making biocompatible nanoparticles with a low potential of toxicity [12].

Not only is this method less damaging to the environment and cheaper, but in many cases, it produces safer and more useful nanoparticles to use in therapy, which is why it is a superior choice to use in medical use [6][12]. This method has received quite an interest as it is eco-friendly, economical and able to manufacture nanoparticles with increased therapeutic value [12][13][6].

This shift of a biological approach is a solution to the limitations of the conventional ways, which normally incorporate harmful chemicals and generate wastes that are polluting and dangerous to the environment and health of human beings. Thus, the use of such green method is gaining more and more appreciation as a better alternative like plant extracts and microbial biomolecules to avoid the environmental and health risks of conventional synthesis methods [16] [17].

This is an approach of binding the biomolecules to the surface of metallic nanoparticles in their manufacture and makes the process more sustainable and cheaper to produce on large-scale manufacture [16][6]. Moreover, it minimizes the number of special equipment and harsh chemicals required, which is why it differs in relation to the usual techniques, where high temperatures or pressures are needed [18].

The reconsideration of using organism like plants, microorganism and even animal materials like chitin and silk has totally changed the method of manufacturing metallic nanoparticles. These natural materials provide more biocompatible alternatives to the conventional chemical processes [16].

Literature Review

The interest in researching the specifics of nanoparticles produced in accordance with the environmentally friendly approaches has grown considerably over the last ten years. The applications of these particles have been many including treatment of bacterial infections, drug and genetic material delivery, cancer, imaging cell, and biological detection [6].

Even though conventional techniques of producing these particles have been successful, they are costly both economically and environmentally. Thus, there has been a need to finding more viable solutions, including green manufacturing practices [6]. The green approach that uses plants, their extracts and microorganisms minimize environmental degradation, decreases the cost of production, and reduces health hazards [6][19].

Due to this reason, it has been adapted to mass production. This approach uses the natural biochemical reactions present in living organisms including the compounds extracted in plants which are useful in reducing metal ions and stabilizing the nanoparticles [6]. This is not only compliant with the principles of green chemistry, but it also improves on the biocompatibility and therapy of nanoparticles [6].

Green synthesis approaches can be described as those that can synthesize nanoparticles that are more stable and can be synthesized in higher rates as compared to those that are synthesized using microorganisms [20]. It is a safe, eco-friendly, and more economically viable solution to the current situation since the toxic chemicals are not utilized in this environmentally friendly method [3]. Moreover, nanoparticles which are environmentally friendly may be naturally biocompatible because they are frequently coated with materials which have a natural source [3][10].

This renders them very suitable in the application in general medical and industrial applications. Recent developments also affirm that these particles including green zinc oxide nanoparticles have powerful antibacterial and anticancer properties [6]. These bioparticles have been widely used in medicine and have created new prospects of therapeutic applications [16]. This underscores the success of green chemistry in producing nanomaterials which are environmentally friendly besides having other enormous implications in the medical sector [21][6].

Zinc oxide nanoparticles synthesized through green processes are less toxic and more bio-degradable than other nanomaterials like gold nanoparticles which are not easily bio-degradable and can accumulate in body tissues [6]. Moreover, synthesis is commonly done without following much of the steps that are typical with chemical methods. It does not need toxic chemicals, generates a minimal amount of waste, and is not dependent on the severe weather conditions or energy intensive features [22].

Biosynthesis is one such new method that can be applied in this area, especially in the case of zinc oxide nanoparticles. In this case, microorganisms and plants exfoliants and stabilizers are taken as natural extracts that are environmentally friendly [23]. Green chemistry is an important measure that is taken in this direction [24] [25]. It enables production of materials that can be modified according to the requisite medical applications to a large scope.

This technique is more preferred to the traditional physical and chemical methods as it does not consider any complicated procedure and it also does not use any harmful substances [26]. The transition to green practices in the production of nanoparticles is a very important move. This is a cheaper and less damaging approach when compared to the conventional approaches [6]. The new principle of biological resources can aid in solving several issues that are related to the older approaches including application of toxic chemicals and the creation of waste that can severely harm the environment and human health.

It is due to this that the green method is becoming even more popular as a better method, as it makes use of natural sources like plant extracts and biomolecules of microbes. This assists in preventing the environmental and health issues related to the conventional manufacturing technique. In this approach, the biomolecules are covalently attached to the metal nanoparticles surface during manufacturing and hence, it is a less costly and less detrimental to large scale manufacturing [27].

This technique greatly decreases the usage of specialized equipment or harsh chemicals, which differentiates it to conventional techniques which use elevated temperatures and high pressures [28]. Actually, the green formulation involves the use of natural and renewable materials like plant extracts, fungi, yeasts, the bacteria and algae which serve as reducing and coating agents. This renders the process of nanoparticle production byproducts-free and environmentally friendly [29].

Table 1. Comparison Between Traditional and Green Synthesis Methods

Parameter	Traditional Synthesis	Green Synthesis
Cost	High	Low
Environmental Safety	Low	High
Biocompatibility	Limited	High

Table 2. Examples of Green Nanoparticles and Their Applications

Nanoparticle Type	Plant Source	Main Applications
Zinc Oxide	Pandanus leaves	Antibacterial
Nickel Oxide	Cinnamon	Antimicrobial

2. Materials and Methods

This review intends to summarize and list the recent advances in the green synthesis of metal nanoparticles and metal oxide nanoparticles. It pays particular attention to description of their characteristics and dwells on their various medical uses. The review also covers the prevailing challenges towards implementing these green materials in medical sphere including regulatory hurdles, mass production capacity and long-term biocompatibility [30].

This is a detailed analysis framework that tries to fill in the gap between the sustainable manufacturing of nanoparticles and their use in the medical sector. This is aimed at developing innovative solutions that can help in solving the world health issues. Moreover, the nanoparticles produced through environmentally friendly procedures are more biocompatible and less toxic usually because they have natural coating materials.

This is why they are most applicable in medical fields and are better than the nanoparticles obtained by traditional approaches [3][31]. The change to green chemistry is justified by the fact that there is a dire need of more sustainable and environmentally friendly ways of synthetic processes as compared to traditional ones, which are usually based on harsh conditions, high costs and lead to environmental pollution [32].

Thus, it is now necessary to adopt sustainable, green, and nature-friendly approaches to manufacturing nanoparticles [33]. The interest in green manufacturing methods is increasing due to the lack of issues that have been related to the traditional methods including the use of harmful chemicals, excessive energy usage, and excessive production cost [28]. As an illustration, physical processes of producing nanoparticles cannot be used in large scale production since they have low yield, consume a lot of energy, and are also costly [6].

On the other hand, the green process is a new alternative that can be used to overcome these issues through the utilization of natural materials to minimize the particle size. This will enable the creation of safe nanoparticles to the body, less expensive, and more eco-friendly [6]. Moreover, this technology allows developing highly efficient nanocarriers that can be used without damaging living organisms or the environment which is absolutely different to the traditional methods of manufacturing [34].

Moreover, green nanoparticles have a high biocompatibility, which increases their properties and provides the economical alternative, which corresponds to the Sustainable Development Goals [28]. Nevertheless, there are some serious problems in this sphere, including the variety of biological sources, and the lack of knowledge about the biochemical processes. This complicates the process standardization and mass production of industries. Thus, it must be noted that these issues should be dealt with to broaden the use of this technology [6].

These concerns are imperative to the expanded implementation of green practices in the medical practice, particularly since they hold a lot of potential in attaining the UN

Sustainable Development Goals [15]. Hence, more attention should be paid to research to comprehend the way biomolecules contribute to the reduction and stability of materials on a narrow level. This will make us come up with efficient and readily replicable green approaches in the future [35][36]. The review attempts to recognize how these techniques address the drawbacks of conventional synthesis techniques, through biochemical reactions which are gentle and safe [17].

3. Results

In spite of these developments, it is extremely difficult to regulate the size, shape and stability of nanoparticles accurately [37]. The challenges that remain to be overcome in order to transition the application of environmentally friendly nanoparticles out of the laboratory into a wider medical context include these [12][38]. The next generation of studies should be done on the internal processes of the entire green synthesis processes, finding new biological and chemical influences that can be used to enhance the methods [39][6].

Another important issue is the development of the application of these methods at the industrial level in order to be able to more tightly control the form of the molecules and make sure that the process can be easily scaled up. As an illustration, the presence of different chemical composition of biological sources, like plants or microorganisms, has a dramatic impact on the properties of the obtained nanoparticles, and thus, the standardization of results is extremely difficult [6].

Moreover, the exact mechanism of various plant molecules in the decrease and stabilization of the molecules during nanoparticle formation is not well understood. This complicates optimization of the manufacturing processes and also the maintenance of standard product quality [40]. Raw material variation and the complexity of interactions of raw materials during a manufacturing process is also widely contributor of batch variability which makes regulation approvals and adoption of medical application to be difficult [3].

In order to overcome these difficulties, there is a need to conduct a lot of research to standardize the manufacturing procedures and to comprehend the complicated interactions between biomolecules and nanoparticles more accurately [40][3]. The methods of analysis, including the high-resolution electron microscopy and the X-ray diffraction analysis, have also developed significantly, providing new possibilities to learn more about the way of how these interactions should take place. This development is advancing us further to control the production of nanoparticles, as it will reveal the specific information concerning the interaction of metal ions with biological molecules [6][11].

Moreover, it is very difficult to shift the environmentally friendly production of nanoparticles in the laboratory to the industrial one. There is more research that is required to streamline reaction conditions, and come up with cost effective and rapid production processes [6][41].

Such zinc oxide nanoparticles might be improved by adding particular biomolecules, linkers, or polymers that would allow them to be more specifically targeted to achieve certain objectives on medical applications, which would lead to the development of better drug delivery systems and more sophisticated imaging technologies [6]. A more ecologically friendly production route to nanoparticles, especially those based on plant extracts, enzymes, and microorganisms, is more sustainable and economical and provides a better bio-nanoparticle with improved biocompatibility and therapeutic capability [24]. Such a method is in line with the concept of green chemistry, ensuring that the adverse effects to the environment are minimized and at the same time the therapeutic effectiveness of the nanoparticles is enhanced [6].

4. Discussion

Moreover, it may be useful to look deeper into biological sources, including the rare plants, organisms in extreme environment, or marine life. Such sources might contain new biomolecules, which can be utilized to design nanoparticles with new shapes and high-functionalities [6]. The study of these fields may result in the identification of nanoparticles with improved physical and chemical characteristics, and enhanced biological response, and creates wide opportunities regarding their application in most medical applications [42].

Nevertheless, in order to guarantee consistent and critical quality in biomedical applications, variations due to the sources of different biologies must be overcome [6]. Moreover, there is a need to gain a better insight into the chemical processes by which particles are reduced and stabilized. The issue of deviation of outcomes is complicated by a deficiency of perfect knowledge of the process that results in the reduction and stabilization of particles in the course of production [43].

Moreover, the enhancement of the characterization techniques, i.e. application of high-resolution transmission electron microscopy and Fourier transform infrared spectroscopy techniques, is of primary importance [6]. These tools allow us to understand more about the multifaceted processes that take place in the manufacturing process and secure more control on production. The manner in which bioactive nanoparticles can be used in the treatment of traditional therapies may also be explored to identify new opportunities of enhancing the effectiveness of treatments and reducing chances of resistance to drugs [44].

Nevertheless, the correlation between nanoparticles and living organisms is complicated and still not comprehensible. Hence, more studies are required to comprehend their effects in the body, their interaction with the tissues, and their possible long-term consequences [45]. Moreover, even though green approaches to nanoparticles manufacturing seem to be promising in the future, the toxicity of such biological particles towards human beings and the environment should be considered urgently.

This would involve a lot of investigative studying on their effects on the environment, as their usage is on the rise in the medical sector [40]. The way out of such concerns is to carry out intensive toxicology tests as well as create strict regulatory systems to achieve sustainable and safe production of greener nanoparticles to be used in medicine.

Moreover, the extrapolation of such techniques to large-scale manufacturing is also a major problem and thus it will be hard to achieve the required standard of consistent quality in medical practice [6]. To a large extent, biological sources are different and having very little knowledge of the chemical processes that regulate the decrease and stabilization of metal ions, it gets hard to enhance manufacturing processes and reproducible with ease [6][46].

State-of-the-art artificial intelligence methods and machine learning algorithms can optimize the conditions of preparation, determine stability of nanoparticles, and improve the overall performance of the material [47]. A combination of such methods of calculations and high-speed experimentation will facilitate the discovery and production of new nanoparticles produced through ecological-friendly processes and designed to suit the unique needs of medical practice.

5. Conclusion

Thus, we still have to perfect the approaches to producing green nanoparticles and pay closer attention to its thorough analysis and widespread testing prior to its application in therapies [6][48][16]. That is to say that we should find more effective methods to establish the action of these particles on cells and what their toxicity mechanisms are.

Moreover, it should be noted that we should establish proper biological models that will assist us in examining the behavior of these particles in the body in detail before we can start to use it safely and efficiently in clinical settings [49]. In order to make the use of nanoparticles safe and effective in medicine, there must be extensive research on the impacts of the nanoparticles on genes and whether it can cause gene mutations particularly when used in large quantities in the body [42].

Moreover, proper instructions and standard procedures should be established in order to enable the safe and successful integration of these advanced nanomaterials in medical practice [6][46]. Moreover, there is a need to design cost-efficient and scalable production processes that will convert the synthesis methods which are eco-friendly, under laboratory testing environment, to products that can be commercially viable. This involves a good knowledge of the parameters of the processes and the effect they have on the characteristics of nanoparticles [8].

Also, the nature of such environmental effects needs to be taken into account during the implementation on a large scale with a specific focus on the sustainability of the sources of raw materials and the organization of the resulting waste [50][6]. Finally, in order to fulfill the maximum therapeutic potential of the nanoparticles produced in environmentally friendly methods, a complex method should be used that would integrate the concepts of green chemistry, the formation of modern materials science, and correct evaluations in the biomedical field [51].

Moreover, green synthesis techniques can be combined with other technologies that are more environmentally friendly, renewable energy sources, and biodegradable materials, which can ensure the production of nanoparticles is more sustainable and environmentally friendly [6]. These advancements are in line with the international process of attaining sustainable development and promoting green practices at all levels of nanomedicine manufacturing [52].

REFERENCES

- [1] M. T. El-Saadony et al "The Impact of Metal/Metal Oxide Nanoparticle Formation Through Green Synthesis from Plants and Microbes: A Thorough Analysis," *Nanotechnology Perceptions*, vol. 20, Aug. 2024, doi: 10.62441/nano-ntp.v20is10.78.
- [2] H. F. Etefa, D. J. Nemera, and F. B. Dejene, "Green Synthesis of Nickel Oxide NPs Incorporating Carbon Dots for Antimicrobial Activities," *ACS Omega*, vol. 8, no. 41, p. 38418, Oct. 2023, doi: 10.1021/acsomega.3c05204.
- [3] K. K. Ilavenil, V. Senthilkumar, and A. Kasthuri, "Green synthesis of metal nanoparticles from three medicinal plants: a review of environmental and health applications," *Discover Catalysis.*, vol. 2, no. 1. Academy of Medicine, Singapore, Mar. 04, 2025. doi: 10.1007/s44344-025-00007-6.
- [4] P. Sharma, N. Bithel, and A. Kaushal, "Green nanoparticle formation toward wound healing, and its application in drug delivery approaches," *European Journal of Medicinal Chemistry Reports*, vol. 6, p. 100088, Sep. 2022, doi: 10.1016/j.ejmcr.2022.100088.
- [5] A. Hussain et al., "Biogenesis of ZnO nanoparticles using Pandanus odorifer leaf extract: anticancer and antimicrobial activities," *RSC Advances*, vol. 9, no. 27, p. 15357, Jan. 2019, doi: 10.1039/c9ra01659g.
- [6] M. T. El-Saadony et al., "Green Synthesis of Zinc Oxide Nanoparticles: Preparation, Characterization, and Biomedical Applications - A Review," *International Journal of Nanomedicine*. Dove Medical Press, p. 12889, Dec. 01, 2024. doi: 10.2147/ijn.s487188.
- [7] A. M. E. Shafey, "Green synthesis of metal and metal oxide nanoparticles from plant leaf extracts and their applications: A review," *Green Processing and Synthesis*, vol. 9, no. 1. De Gruyter, p. 304, Jun. 18, 2020. doi: 10.1515/gps-2020-0031.
- [8] J. Singh, T. Dutta, K. Kim, M. Rawat, P. Samddar, and P. Kumar, "'Green' synthesis of metals and their oxide nanoparticles: applications for environmental remediation," *Journal of Nanobiotechnology*, vol. 16, no. 1. BioMed Central, Oct. 30, 2018. doi: 10.1186/s12951-018-0408-4.

- [9] D. Kavaz, H. Umar, and M. R. Aliyu, "Green Synthesized Metallic Oxide Nanomaterials for Diverse Applications," *NanoWorld Journal*, vol. 8, no. 1, Jan. 2022, doi: 10.17756/nwj.2022-096.
- [10] A. I. Osman et al., "Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural, and food applications: A review," *Environmental Chemistry Letters*, vol. 22, no. 2. Springer Science+Business Media, p. 841, Jan. 20, 2024. doi: 10.1007/s10311-023-01682-3.
- [11] H. R. El-Seedi et al., "Updated Review of Metal Nanoparticles Fabricated by Green Chemistry Using Natural Extracts: Biosynthesis, Mechanisms, and Applications," *Bioengineering*, vol. 11, no. 11. Multidisciplinary Digital Publishing Institute, p. 1095, Oct. 30, 2024. doi: 10.3390/bioengineering11111095.
- [12] S. Thakur and R. Gupta, "Medicinal plants derived green synthesis of nanoparticles: classification, methods, applications and environmental impacts," *Nanotechnology for Environmental Engineering*, vol. 10, no. 2, Apr. 2025, doi: 10.1007/s41204-025-00421-z.
- [13] S. Sagadevan, I. Fatimah, J. A. Lett, M. Z. Rahman, E. Léonard, and W. Oh, "Eco-friendly green approach of nickel oxide nanoparticles for biomedical applications," *Open Chemistry*, vol. 21, no. 1, Jan. 2023, doi: 10.1515/chem-2023-0141.
- [14] P. Rauwel, "Emerging Trends in Nanoparticle Synthesis Using Plant Extracts for Biomedical Applications," *Global Journal of Nanomedicine*, vol. 1, no. 3, Mar. 2017, doi: 10.19080/gjn.2017.01.555562.
- [15] S. T. Shah et al., "Nature's nanofactories: biogenic synthesis of metal nanoparticles for sustainable technologies," *Green Chemistry Letters and Reviews*, vol. 18, no. 1, Mar. 2025, doi: 10.1080/17518253.2024.2448171.
- [16] R. Ullah et al., "A comprehensive overview of fabrication of biogenic multifunctional metal/metal oxide nanoparticles and applications," *Reviews in Inorganic Chemistry*, Aug. 2024, doi: 10.1515/revic-2024-0031.
- [17] R. Álvarez-Chimal and J. Arenas-Alatorre, "Green Synthesis of Nanoparticles: A Biological Approach," in *IntechOpen eBooks*, IntechOpen, 2023. doi: 10.5772/intechopen.1002203.
- [18] V. Soni et al., "Sustainable and green trends in using plant extracts for the synthesis of biogenic metal nanoparticles toward environmental and pharmaceutical advances: A review," *Environmental Research*, vol. 202. Elsevier BV, p. 111622, Jul. 07, 2021. doi: 10.1016/j.envres.2021.111622.
- [19] K. Hajra, D. Maity, and S. Saha, "Recent Advancements of Metal Oxide Nanoparticles and their Potential Applications: A Review," *Advanced Materials Letters*, vol. 15, no. 1. International Association of Advanced Materials, p. 2401, Dec. 20, 2023. doi: 10.5185/amlett.2024.011740.
- [20] V. Girotra, P. Kaushik, and D. Vaya, "Exploring sustainable synthesis paths: a comprehensive review of environmentally friendly methods for fabricating nanomaterials through green chemistry approaches," *TURKISH JOURNAL OF CHEMISTRY*, vol. 48, no. 5. Scientific and Technological Research Council of Turkey (TUBITAK), p. 703, Oct. 24, 2024. doi: 10.55730/1300-0527.3691.
- [21] N. S. Alsaiani et al., "Plant and Microbial Approaches as Green Methods for the Synthesis of Nanomaterials: Synthesis, Applications, and Future Perspectives," *Molecules*, vol. 28, no. 1. Multidisciplinary Digital Publishing Institute, p. 463, Jan. 03, 2023. doi: 10.3390/molecules28010463.
- [22] J. Iqbal et al., "Green synthesis of zinc oxide nanoparticles using *Elaeagnus angustifolia* L. leaf extracts and their multiple in vitro biological applications," *Scientific Reports*, vol. 11, no. 1, Oct. 2021, doi: 10.1038/s41598-021-99839-z.
- [23] A. E. Golli, S. Contreras, and C. Dridi, "Bio-synthesized ZnO nanoparticles and sunlight-driven photocatalysis for environmentally-friendly and sustainable route of synthetic petroleum refinery wastewater treatment," *Scientific Reports*, vol. 13, no. 1, Nov. 2023, doi: 10.1038/s41598-023-47554-2.
- [24] J. Nandhini, K. Elumalai, and S. Rajeshkumar, "Green synthesis of zinc oxide nanoparticles: Eco-friendly advancements for biomedical marvels," *Resources Chemicals and Materials*, vol. 3, no. 4, p. 294, Jun. 2024, doi: 10.1016/j.recmm.2024.05.001.
- [25] S. Arafat et al., "Phyto-assisted synthesis of zinc oxide nanoparticles using *Bauhinia variegata* buds extract and evaluation of their multi-faceted biological potentials," *Scientific Reports*, vol. 14, no. 1, Sep. 2024, doi: 10.1038/s41598-024-72250-0.
- [26] A. Raza et al., "Polyalthia longifolia-mediated green synthesis of zinc oxide nanoparticles: characterization, photocatalytic and antifungal activities," *RSC Advances*, vol. 14, no. 25, p. 17535, Jan. 2024, doi: 10.1039/d4ra01035c.

- [27] A. Farooq et al., "Green Chemistry Based Synthesis of Zinc Oxide Nanoparticles Using Plant Derivatives of *Calotropis gigantea* (Giant Milkweed) and Its Biological Applications against Various Bacterial and Fungal Pathogens," *Microorganisms*, vol. 10, no. 11, p. 2195, Nov. 2022, doi: 10.3390/microorganisms10112195.
- [28] D. Kulkarni et al., "Biofabrication of nanoparticles: sources, synthesis, and biomedical applications," *Frontiers in Bioengineering and Biotechnology*, vol. 11. Frontiers Media, May 02, 2023. doi: 10.3389/fbioe.2023.1159193.
- [29] E. Matei et al., "ZnO nanostructured matrix as nexus catalysts for the removal of emerging pollutants," *Environmental Science and Pollution Research*, vol. 30, no. 54. Springer Science+Business Media, p. 114779, Nov. 03, 2023. doi: 10.1007/s11356-023-30713-3.
- [30] G. Dutta, S. kumar Chinnaiyan, A. Sugumaran, and D. Narayanasamy, "Sustainable bioactivity enhancement of ZnO–Ag nanoparticles in antimicrobial, antibiofilm, lung cancer, and photocatalytic applications," *RSC Advances*, vol. 13, no. 38, p. 26663, Jan. 2023, doi: 10.1039/d3ra03736c.
- [31] D.-M. Radulescu, V.-A. Surdu, A. Ficai, D. Ficai, A. M. Grumezescu, and E. Andronescu, "Green Synthesis of Metal and Metal Oxide Nanoparticles: A Review of the Principles and Biomedical Applications," *International Journal of Molecular Sciences*, vol. 24, no. 20. Multidisciplinary Digital Publishing Institute, p. 15397, Oct. 20, 2023. doi: 10.3390/ijms242015397.
- [32] H. Singh et al., "Revisiting the Green Synthesis of Nanoparticles: Uncovering Influences of Plant Extracts as Reducing Agents for Enhanced Synthesis Efficiency and Its Biomedical Applications," *International Journal of Nanomedicine*. Dove Medical Press, p. 4727, Aug. 01, 2023. doi: 10.2147/ijn.s419369.
- [33] B. Naiel, M. Fawzy, A. E. D. Mahmoud, and M. W. A. Halmy, "Sustainable fabrication of dimorphic plant derived ZnO nanoparticles and exploration of their biomedical and environmental potentialities," *Scientific Reports*, vol. 14, no. 1, Jun. 2024, doi: 10.1038/s41598-024-63459-0.
- [34] M. S. Samuel et al., "A Review on Green Synthesis of Nanoparticles and Their Diverse Biomedical and Environmental Applications," *Catalysts*, vol. 12, no. 5. Multidisciplinary Digital Publishing Institute, p. 459, Apr. 20, 2022. doi: 10.3390/catal12050459.
- [35] K. Parveen, V. Banse, and L. Ledwani, "Green synthesis of nanoparticles: Their advantages and disadvantages," *AIP conference proceedings*, Jan. 2016, doi: 10.1063/1.4945168.
- [36] A. Rónavári et al., "Green Silver and Gold Nanoparticles: Biological Synthesis Approaches and Potentials for Biomedical Applications," *Molecules*, vol. 26, no. 4. Multidisciplinary Digital Publishing Institute, p. 844, Feb. 05, 2021. doi: 10.3390/molecules26040844.
- [37] H. J. Fatih, M. Ashengroph, A. Sharifi, and M. M. Zorab, "Green-synthesized α -Fe₂O₃-nanoparticles as potent antibacterial, anti-biofilm and anti-virulence agent against pathogenic bacteria," *BMC Microbiology*, vol. 24, no. 1, p. 535, Dec. 2024, doi: 10.1186/s12866-024-03699-2.
- [38] A. B. T. Mawthoh, D. Seram, and H. J. Watt, "Green Synthesized Plant-based Nanotechnology: Cutting Edge Innovation Fostering Sustainability and Revolutionizing Agriculture," *E3S Web of Conferences*, vol. 453, p. 1018, Jan. 2023, doi: 10.1051/e3sconf/202345301018.
- [39] B. Rajalakshmi et al., "Bio-inspired Nanomaterial's for Energy Harvesting and Storage: A Green Approach," *E3S Web of Conferences*, vol. 552, p. 1122, Jan. 2024, doi: 10.1051/e3sconf/202455201122.
- [40] S. Patil and R. Chandrasekaran, "Biogenic nanoparticles: a comprehensive perspective in synthesis, characterization, application and its challenges," *Journal of Genetic Engineering and Biotechnology*, vol. 18, no. 1. Elsevier BV, p. 67, Oct. 26, 2020. doi: 10.1186/s43141-020-00081-3.
- [41] F. Arshad et al., "Bioinspired and Green Synthesis of Silver Nanoparticles for Medical Applications: A Green Perspective," *Applied Biochemistry and Biotechnology*, vol. 196, no. 6. Springer Science+Business Media, p. 3636, Sep. 05, 2023. doi: 10.1007/s12010-023-04719-z.
- [42] P. Das, S. Ghosh, and B. Nayak, "Phyto-fabricated Nanoparticles and Their Anti-biofilm Activity: Progress and Current Status," *Frontiers in Nanotechnology*, vol. 3, Oct. 2021, doi: 10.3389/fnano.2021.739286.
- [43] M. Murali et al., "Zinc oxide nanoparticles prepared through microbial mediated synthesis for therapeutic applications: a possible alternative for plants," *Frontiers in Microbiology*, vol. 14. Frontiers Media, Sep. 05, 2023. doi: 10.3389/fmicb.2023.1227951.
- [44] A. Sharma et al., "Biogenic Zinc Oxide Nanoparticles: An Insight into the Advancements in Antimicrobial Resistance," *ECS Journal of Solid State Science and Technology*, vol. 13, no. 4, p. 47002, Apr. 2024, doi: 10.1149/2162-8777/ad397f.

- [45] A. M. Salih et al., "Biosynthesis of zinc oxide nanoparticles using *Phoenix dactylifera* and their effect on biomass and phytochemical compounds in *Juniperus procera*," *Scientific Reports*, vol. 11, no. 1, Sep. 2021, doi: 10.1038/s41598-021-98607-3.
- [46] R. Nain, H. Patel, M. Chahar, S. Kumar, D. Rohilla, and M. Pal, "Biosynthesized metallic nanoparticles for sustainable environmental remediation: mechanisms, applications, and future perspectives," *Discover Chemistry*, vol. 2, no. 1, May 2025, doi: 10.1007/s44371-025-00203-1.
- [47] S. Hosny, G. A. Gaber, M. S. Ragab, M. A. Ragheb, M. Anter, and L. Z. Mohamed, "A Comprehensive Review of Silver Nanoparticles (AgNPs): Synthesis Strategies, Toxicity Concerns, Biomedical Applications, AI-Driven Advancements, Challenges, and Future Perspectives," *Arabian Journal for Science and Engineering*, Sep. 2025, doi: 10.1007/s13369-025-10612-0.
- [48] S. A. Atanda, R. O. Shaibu, and F. O. Agunbiade, "Nanoparticles in agriculture: balancing food security and environmental sustainability," *Discover Agriculture*, vol. 3, no. 1, Feb. 2025, doi: 10.1007/s44279-025-00159-x.
- [49] H. R. El-Seedi et al., "Metal nanoparticles fabricated by green chemistry using natural extracts: biosynthesis, mechanisms, and applications," *RSC Advances*, vol. 9, no. 42. Royal Society of Chemistry, p. 24539, Jan. 01, 2019. doi: 10.1039/c9ra02225b.
- [50] F. Khan, M. Shariq, M. Asif, M. A. Siddiqui, P. Malan, and F. Ahmad, "Green Nanotechnology: Plant-Mediated Nanoparticle Synthesis and Application," *Nanomaterials*, vol. 12, no. 4. Multidisciplinary Digital Publishing Institute, p. 673, Feb. 17, 2022. doi: 10.3390/nano12040673.
- [51] H. Saravanan et al., "Exploring nanocomposites for controlling infectious microorganisms: charting the path forward in antimicrobial strategies," *Frontiers in Pharmacology*, vol. 14. Frontiers Media, Sep. 27, 2023. doi: 10.3389/fphar.2023.1282073.
- [52] U. P. Panigrahy, K. K. Bharti, S. Gupta, and B. Saha, "Development of Eco-Friendly Nanoparticles for Sustainable Drug Delivery: A Comprehensive Review," *Advances in health sciences research/Advances in Health Sciences Research*. Atlantis Press, p. 139, Jan. 01, 2025. doi: 10.2991/978-94-6463-813-4_11.