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Biogenic synthesis, characterization, and applications of Zinc Oxide (ZnO) nanoparticles derived from diverse plant components - a review

Kavya Prakash K. M. and Prakash V.*

Department of PG Studies & Research in Physics, Payyanur College, Kannur University, Edat Kannur, Kerala, 670327

Abstract—The synthesis of metallic nanoparticles from various parts of plants, such as seeds, roots, leaves, flowers, and fruits, has been extensively documented in the literature. Among the different synthesis approaches, green synthesis is a secure, regulated, and environmentally friendly technique for producing nanoparticles. In contrast, the alternative widely employed method, chemical synthesis, has a negative environmental impact due to the discharge of hazardous and highly reactive substances into the surroundings. Consequently, this present review focuses on diverse synthesis methods for nanoparticles, with a specific emphasis on the green approach employing various plant extracts. Commonly employed agents for biosynthesis include extracts from plant parts microorganisms, and proteins, all of which act as reducing agents. Within this review, we delve into the intricacies of synthesis techniques, characterization procedures, inherent properties, and the versatile applications of ZnO nanoparticles that are synthesized utilizing various parts of plants.

Keywords: *Zinc oxide nanoparticles; Green synthesis; Antibacterial property; XRD; SEM; Antimicrobial property*

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1. Introduction

Nanoparticles prepared via biological methods have received more attention because of their prominent biological characteristics and biomedical applications. Among these biologically prepared nanoparticles, metal oxide nanoparticles show potential and far-ranging prospects for the biomedical field notably for antibacterial and antimicrobial properties, anticancer properties, drug delivery, cell imaging, sensing, etc. [1]. ZnO is one of the most important semiconductor metal oxide nanoparticles and is popularly used in various fields due to its unique characteristics. ZnO is nearly insoluble in water and commonly found in three different crystal structures such as wurtzite, zinc blende, and rock salt. The thermodynamically stable structure of ZnO is wurtzite. ZnO is widely used in personal care products such as cosmetics, Ointments, baby powder, barrier creams to treat diaper rashes, calamine lotions, antidandruff shampoos, and antiseptic ointments because of their strong UV light absorption property. Several toxic materials affect the aquatic ecosystem and further lead to environmental pollution. The semiconductor-based photocatalyst can be a solution for such environmental pollution. ZnO is an inorganic semiconducting material well known for its distinctive electrical and optical properties. There are several well-reported ZnO nanoparticle synthesis methods such as the precipitation method, microwave method, microemulsion method, solvothermal method, andnon-hydrolytic solution [2]. The use of toxic chemicals as capping agents, tedious procedures, and rigorous experimental conditions are the major concerns while synthesizing nanoparticles. Biosynthesis, a new and innovative approach for nanoparticle synthesis using plant parts and microorganisms is emerging nowadays. Biosynthesis of ZnO nanoparticles from leaf extracts of various plants such as neem, aloe vera, papaya, curry leaf, hibiscus, Coriandrum, etc. have been reported.

In this review, we focus on the synthesis of ZnO using various plants and study how it is beneficial for various applications. Fig 1 below shows the various applications of ZnO nanoparticles. Biosynthesis methods have also been adopted for the reutilization of agricultural waste including seeds, peels, and so on [3].

2. Synthesis of Nanomaterials

The synthesis of metal oxide nanoparticles is classified into two groups which are the top-down approach and the bottom-up approach. Van der Waals bonding is involved in the top-down methods, and it requires very large energy at the input. Laser

*Corresponding author.
E-mail address: prakashamv@gmail.com (Dr. V. Prakash)

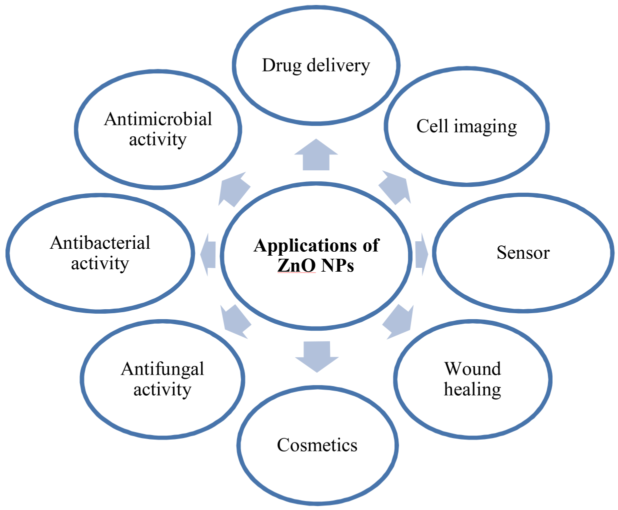

Figure 1: Applications of ZnO nanoparticles.

ablation, mechanical milling, and sputtering are the commonly used top-down methods. Small-sized particles cannot be involved in this method. The assembling or aggregation of atoms or molecules to form a bulk material is the basic principle of bottom-up methods. Conventional methods such as chemical and physical methods and biological methods using bacteria, fungi, plant extracts, and algae come under the bottom-up approach. Ionic or covalent bonding is involved in the bottom-up methods. Sol-gel method, hydrothermal method, spray pyrolysis, and physical and chemical vapor deposition are the commonly used bottom-up methods [4].

In general, we can say that nanoparticles are synthesized by using chemical and physical methods. However, chemical methods lead to the formation of substances that are harmful to the environment. Physical methods employ large amounts of energy which is less economic. Hence a new and innovative approach is needed for the safe production of nanomaterials. Biological synthesis is a safer, eco-friendly, cost-effective method for nanomaterial fabrication and is the best alternative to physical and chemical methods [5]. The conventional method requires additional capping and stabilizing agents. In biosynthesis, plant extracts themselves act as a capping and stabilizing agent.

2.1 Biosynthesis of nanomaterials

When comparing synthesis methods, the preference for green approaches over chemical techniques is rooted in their ability to mitigate the release of harmful substances associated with chemical methods [6]. Utilizing plant components like fruits, peels, and leaves, as well as microorganisms, these environmentally conscious green methods offer an advantageous alternative. The array of microorganisms applied in these methods includes bacteria, fungi, and algae, among others. In the realm of green methodologies, plants shine particularly brightly due to their inherent biomedical potential. This is underlined by their capacity toyield biosynthesized nanoparticles on a significant scale, brimming with possibilities for both medical and industrial applications [7]. An established example of this is the controlled and ecologically friendly synthesis achieved through plant extracts for metallic nanoparticles. In contrast, Chemical synthesis often necessitates harsh conditions in the nanoparticle production process. This, coupled with the detrimental impact of chemical solvents on the environment, highlights the limitations of chemical techniques. In this context, the introduction of plant extracts as stabilizing, capping, and hydrolytic agents offers a promising solution that aligns with environmentally sustainable practices. Moreover, the selection of plants for this study holds additional significance, as they boast a myriad of biomedical applications and exceptional antimicrobial and antibacterial properties [8]. Through a confluence of green principles and their inherent attributes, these plants emerge as potential cornerstones for the development of innovative and eco-friendly approaches in the synthesis of nanoparticles.

3. Scientific Studies

Literature reviews embark on a comprehensive exploration of the biosynthesis of zinc oxide nanoparticles using various medicinal plants. By examining the existing body of knowledge, we aim to elucidate the diverse methodologies used in this novel synthesis approach and highlight the role of plant-derived compounds in governing the size, shape, and stability of ZnO nanoparticles. Furthermore, we seek to discern the underlying mechanisms that govern the bio-reduction process and the interactions between plant constituents and metal ions during nanoparticle formation. As we navigate through the literature, we critically analyze the various plants utilized for zinc oxide nanoparticle biosynthesis, discussing their phytochemical composition, potential bioactivity, and efficiency in nanoparticle synthesis.

In the study conducted by Lolly et al. in 2021, an investigation was carried out to examine the adsorption and photocatalytic properties of ZnO nanoparticles, which were synthesized using aloe vera leaf extract. The researchers explored the mechanisms behind the adsorption process using various kinetic models, such as the intra-particle diffusion model, and compared the outcomes of Legergren's pseudo-first order and pseudo-second-order methods. These methods were employed to better understand how ZnO nanoparticles interact with their surroundings. Furthermore. The structural characteristics of the ZnO nanoparticles were analyzed through X-ray diffraction analysis, revealing a distinctive crystalline structure characterized by a hexagonal wurtzite phase. To determine the particle size, both the Scherrer method and the Williamson-Hall method were employed. The results yielded an average particle size of 12.6 nm when using the Scherrer method and 19.27 nm when utilizing the Hall method. This dual approach in particle size analysis provided a comprehensive perspective on the size distribution of the ZnO nanoparticles. To confirm the formation of ZnO nanostructures, the researchers turned to field emission scanning electron microscopy (FE-SEM) characterization. This technique allowed them to visualize and analyze the surface morphology of the synthesized nanoparticles, providing visual evidence of their structural attributes. Additionally, the study delved into the electronic properties of ZnO nanoparticles, particularly their band gap energy. By employing UV-visible spectroscopy, the researchers determined that the band gap of ZnO was calculated to be 3.19 Ev. This band gap value is crucial as it signifies the energy required for an electron to transition from the valence band to the conduction band, thereby influencing the material's optical and electronic behavior [9].

The research conducted by Sivalingam et al. in 2021 focuses on an economical and environmentally friendly approach for synthesizing ZnO nanoparticles using neem leaf extract and explores its application in nanofluids. The unique aspect of this study lies in the utilization of neem leaves, which serve the dual purpose of acting as both capping and they were reducing agents during the nanoparticle synthesis process. This ingenious approach results in ZnO nanoparticles with favorable thermal transport properties when incorporated into nanofluids, demonstrating potential benefits for various thermal management applications. The researchers employed two distinct methods to synthesize the Nanopowder samples: the combustion en-route method and the sol-gel method. In the combustion method, a combination of zinc nitrate hexahydrate and glycine was employed as precursor materials. On the other hand, the sol-gel method utilized zinc acetate dihydrate. These methods provided two different routes for producing ZnO nanoparticles, each with its own set of characteristics and potential applications. To quantify the size of the nanoparticles produced through these methods, the researchers employed Scherrer's formula for particle size determination. This approach allowed them to calculate the particle size separately for each synthesis method. In the case of the sol-gel technique, the calculatedparticle size was 32 nm, while the combustion method resulted in slightly larger particles with a size of 36nm. This particle size information offers valuable insights into the physical attributes of the synthesized ZnO nanoparticles and helps to understand the effects of the different synthesis approaches [10].

The study conducted by Priyadharsini et al. in 2021 presents a novel approach to synthesizing ZnO and manganese-dopedZnO nanoparticles using Carica papaya leaf extract, with a specific focus on their potential antibacterial applications. The researchers harnessed the natural properties of Carica papaya leaf extract to mediate the synthesis of these nanoparticles, which were intended to possess antibacterial properties for potential therapeutic purposes. In this investigation, ZnO nanoparticles were synthesized via the Co-precipitation method, utilizing the leaf extract of Carica papaya as a crucial component in the synthesis process. To verify the successful formation of ZnO nanoparticles researchers used XRD and FTIR characterization techniques. These techniques were employed to validate the presence and characteristics of the ZnO nanoparticles. The XRD analysis unveiled the distinctive hexagonal wurtzite structure of both ZnO and Mn-doped ZnO nanoparticles, underscoring their crystalline nature. The antibacterial property of the synthesized ZnO nanoparticles was evaluated through the agar well diffusion method. This method involves the introduction of nanoparticles into agar wells and observing their inhibitory effect on bacterial growth. Both gram-positive and gram-negative bacteria were subjected to this assay to comprehensively assess the antibacterial properties of the nanoparticles. The study's findings concluded that Mn-doped ZnO nanoparticles, possessing an average crystalline size of 8.49 nm, exhibited superior antibacterial activity compared to ZnO nanoparticles, which had a marginally smaller average size of 7.75 nm. This comparison suggests that the introduction of manganese into the ZnO structure enhanced its antibacterial potential, potentially due to altered surface properties or other structural; modifications [11], [12].

In 2021, Menna et al. introduced an innovative and safe approach for producing ZnO nanoparticles, leveraging the natural properties of psidium guava leaves as a reducing agent. The study further explored the application of these nanoparticles to impart multifunctional qualities to cellulosic fabrics, highlighting their potential in diverse contexts. By tapping into the reducing capabilities of guava leaf extracts, the researchers aimed to develop a straightforward and eco-friendly method for ZnO nanoparticle synthesis. The investigation involved two types of guava leaf extracts: water extract and ethanol; extract. Both were utilized as reducing agents in the nanoparticle synthesis process. To unveil the characteristics of the synthesized nanoparticles, the research employed a comprehensive array of characterization techniques. This included a particle size analyzer to gauge size distribution, TEM to visualize nanoparticle morphology, XRD to study crystalline structure, and thermogravimetric analysis to investigate thermal properties. The multi-pronged approach offered insights into the particles' physical attributes and their potential applications. One of the interesting aspects of the study was the exploration of the impact of pH levels on the synthesis of ZnO nanoparticles. The researchers systematically investigated how variations in pH influenced the nanoparticle synthesis process. Notably, the study discovered that elevating the pH of the medium led to a reduction in the size of the synthesized nanoparticles. This observation underscores the role of P H as a crucial factor in controlling the size and properties of the nanoparticles produced using guava leaf extracts. Additionally, the research unveiled a noteworthy distinction between nanoparticles synthesized using guava leaf extract in water versus ethanol across different p H conditions. The particle size of those synthesized in water was found to be higher in comparison to the ones synthesized in ethanol. This comparative analysis underscored the influence of the extraction solvent and medium p H on the resultant nanoparticles' characteristics [13].

Khursheed et al., (2020) reported a novel concept for manufacturing ZnO nanoparticles by using an environmentally friendly approach to the aloe vera leaf extract. Study exploiting the reducing and capping potential of aloe vera leaf extract. XRD (X-ray diffraction), EDX (Energy Dispersive X-ray analysis), SEM (Scanning Electron Microscopy), UV-Vis (Ultraviolet-Visible spectroscopy), and FTIR (Fourier Transform Infrared Spectroscopy) are the various techniques used in this study for the evaluation of the structure and morphology of ZnO nanoparticles. The study explained aloe vera's medical benefits, notably its anti-inflammatory, anti-arthritic, and antibacterial properties. ZnO nanoparticles synthesized using aloe vera leaf extract have been used to remove arsenic and sulfur from water and in dental applications [14].

In 2020, Debika et al. Investigated the impact of biochemical compounds present in aloe vera and lemon extracts on the utilization of these natural extracts, harnessing their inherent bioactive components to facilitate the synthesis of ZnO nanoparticles. Both aloe vera and lemon extract contain an array of bioactive compounds such as aloin, saccharides, proteins, enzymes, and phenols. And flavonoids, which were identified as key players in the reduction process necessary for ZnO nanoparticle synthesis. The primary focus of the research was to explore how these bioactive compounds with aloe vera, and lemon extracts acted as reducing agents during the preparation of ZnO nanoparticles. The inherent properties of these compounds, particularly their reducing potential, were harnessed to facilitate the conversion of precursor materials into ZnO nanoparticles. To substantiate their findings, the prepared nanoparticle samples underwent comprehensive characterization using a range of spectroscopic techniques. X-ray Diffraction (XRD) analysis was used to examine the crystalline nature of the nanoparticles. Energy Dispersive X-ray analysis (RDX) offered insights into the elemental composition of the synthesized samples. Field Emission Scanning Electron Microscopy (FESEM) provided a detailed image of the nanoparticle morphology. The study's observations unveiled distinct characteristics of aloe vera and lemon extracts. The lemon extract was found to be rich in various bioactive components, including carboxylic acids, polyols, and proteins. On the other hand, aloe vera extract exhibited an abundance of phenolic compounds. These differential compositions contribute to the distinct reduction potential of each extract, which in turn influences the efficiency of ZnO nanoparticle synthesis [15].

The leaf extract of a medicinally essential plant such as aloe vera was used by Seifunnisha et al., (2020) to prepare ZnO nanoparticles. A study was used to check the influence of aloe vera on the enhancement of photocatalytic degradation and antibacterial activity of ZnO by the sol-gel synthesis method. In this work, the sol-gel synthesis method was employed for the synthesis of ZnO nanoparticles using aloe vera as dispersing media. Synthesized samples were characterized by XRD (X-ray diffraction), FESEM (Field Emission Scanning Electron Microscopy), UV-DRS (), and FTIR (Fourier Transform Infrared Spectroscopy). These techniques reveal the structural, morphological, optical, and biological properties of ZnO nanoparticles. The study concluded that the lower crystallite size value will give a higher surface-to-volume ratio which results in increasing photocatalytic degradation efficiency. The photocatalytic degradation efficiency of 95% was achieved in this work [16].

Revathi et al. (2020) propose an innovative and eco-friendly approach to synthesizing ZnO nanoparticles by utilizing the extract of Azadirachta indica, commonly known as neem. This study specifically proposed the applications of these neem-synthesizedZnO nanoparticles in latent fingermark development. Offering a greener alternative for forensicpurposes. The research sought to harness the natural properties of neem extract as a reducing agent to fabricate ZnO nanoparticles with potential applications in fingerprint enhancement on non-porous surfaces. To achieve this, the synthesis process involved the utilization of neem extract as a reducing agent during the formation of ZnO nanoparticles. This approach put forward the green and sustainable aspects of nanoparticle production, minimizing the use of conventional chemical agents. The resultant product was a yellow-colored powder composed of neem-synthesized ZnO nanoparticles. The study's core focus revolved around the potential application of these neem-synthesizedZnO nanoparticles for latent fingermark development on non-porous surfaces. The nanoparticles' distinct properties were evaluated in this context, and the study concluded that they showed promise in enhancing latent fingerprints. This suggests that the synthesized ZnO nanoparticles could potentially serve as an effective tool in forensic investigations by improving the visibility and resolution of latent fingerprints on surfaces that are typically difficult to work with [17].

Kanika et al., (2020) identified the eco-friendly synthesis of ZnO nanoparticles using Carica papaya leaf extract and their applications. The nanoparticles were characterized using XRD (X-ray diffraction), FTIR (Fourier Transform Infrared Spectroscopy), SEM-EDX (Scanning Electron Microscopy- Energy Dispersive X-ray spectroscopy), Dynamic light scattering (DLS) analyzer, and UV-Vis (Ultraviolet-Visible spectroscopy) spectroscopic techniques. Antifungal studies were conducted against S. sclerotiorum, R. necatrix, and Fusarium species. In this study formed nanoparticles were semi-spherical and monoclinic non-spherical with an average particle size of 14 nm. The study revealed the role of ZnO nanoparticles in seed germination, 75% of ZnO nanoparticles are most suitable for improving the root and shoot length. ZnO nanoparticles can be used to control the reproduction of pathogenic fungi which are harmful to plants [18].

Minha et al., (2020) research exhibits the antibacterial and antimicrobial properties ofZnO nanoparticles synthesized using leaf extract of cassia fistula and meliaAzadarach. The structural and optical properties of obtained nanoparticles were investigated by XRD (X-ray Diffraction), FTIR (Fourier Transform Infrared Spectroscopy), SEM (Scanning Electron Microscopy), UV-Vis (Ultraviolet-Visible spectroscopy), and dynamic light scattering (DLS) techniques. This study used the paper disc diffusion method to examine the antibacterial potential of ZnO nanoparticles against E. coli and S. aureus. The formation of ZnO nanoparticles indicates a change in the color of the reaction mixture from brown to white. UV peaks were observed at 320 and 324nm.SEM shows the spherical shape of nanoparticles and XRD pattern matching with the JCPDS (Joint Committee on Powder Diffraction Standards) card for the ZnO nanoparticles. The study concluded that nanoparticles synthesized using extracts of medicinal plants can have a lot of useful applications in the medical field [19].

In 2019, the research conducted by Saurabh Sharma et al. offered valuable insights into the influence of ZnO nanoparticle size and shape on their antimicrobial and photocatalytic properties, although an environmentally friendly approach. The study harnessed a green synthesis method, utilizing aloe vera leaf extract and an aqueous solution of zinc acetate dihydrate, to create ZnO nanoparticles with varying shapes and sizes. This approach not only aligned with sustainable practices but also shed light on the potential applications of differently shaped nanoparticles in the field of antimicrobial and photocatalytic activities. Various characterization techniques were used to analyze the synthesized nanoparticles. One of the key findings of the study was the discovery of how the concentration of the precursor solution influenced the shapes of the nanoparticles. This observation highlighted the delicate interplay between precursor concentration and the resulting nanoparticle morphology, revealing a link between synthesis parameters and the resultant characteristics of the nanoparticle. This observation highlighted the delicate interplay between precursor concentration and the resulting nanoparticle morphology, revealing a link between synthesisparameters and the resultant characteristics of the nanoparticles. The study's outcomes also encompassed the determination of nanoparticle size, which ranged from 40 to 180 nm. This span of sizes highlighted the versatility achievable through the synthesis method, and the subsequent assessment of antibacterial activities against three types of bacteria demonstrated the potential utility of these nanoparticles in combating microbial infections. To quantify the crystalline size of the synthesized nanoparticles, the study employed Scherrer's formula, which is a widely used technique for such calculations. This calculation provided insights into the dimensions of the crystalline structures within the nanoparticles [20].

Kwadena et al., (2019) Research addressing the evaluation of antibacterial efficiency of biosynthesis of ZnO nanoparticles using fresh leaf and stem extract of Carica papaya. SEM, TEM, and FTIR techniques were used for the characteristics study of the samples. Antibacterial activity of the prepared samples from stem and leaf extract of papaya was tested against five microbes such as Staphylococcus aureus, Escherichia coli, Acinetobacter baumanni, Exiguobacterium aquaticum, and Klebsielia pneumoniae. Formed nanoparticles are petal-like in shape with an average particle size range between 54-97 nm. The results revealed that the antibacterial activity of ZnO nanoparticles prepared using stem extract of Carica papaya is higher than that of the same prepared using leaf extract of Carica papaya. In their analysis, these methods are an effective substitute for chemical methods and ZnO nanoparticles showed a positive antibacterial result towards the selected microbes [21].

Khaing et al. (2018) conducted an insightful investigation into the green synthesis of zinc oxide nanoparticles through the utilization of tropical plants. This study delved into the process of fabricating zinc oxide nanoparticles by employing extracts from neem leaves and golden shower plants. The focus was on the inherent properties of these plants to mediate the synthesis of nanoparticles in an environmentally friendly manner. The neem and golden shower extracts, enriched with bioactive compounds, played a pivotal role in facilitating the reduction of zinc ions and subsequently guiding their transformation into zinc oxide nanoparticles. This green approach to nanoparticle synthesis is aligned with sustainable practices, minimizing the need for conventional chemical methods. To study the properties of prepared nanoparticles advanced analytical techniques were employed. Ultraviolet-visible spectroscopy (UV-Vis) was utilized to unravel the nanoparticles' optical properties. Fourier Transform Infrared Spectroscopy (FTIR) enabled the identification of functional groups present on the nanoparticles' surfaces. Energy Dispersive X-ray Spectroscopy (EDX) provided insights into the elemental composition, while X-ray Diffraction analysis revealed their crystalline structure. The study findings extended to the potential applications of these bio-functionalized zinc oxide nanoparticles. The interaction of the extracted chemicals with zinc ions, leading to the formation of nanoparticles, set the stage for future utilization in nano-drug production. This implication underscores the multifunctional capabilities in the field of medicine and pharmaceuticals [22].

Seerangaraj et al. (2017) investigated the photocatalytic degradation of water pollutants using the green synthesis of ZnO nanoparticles. Chemical pollutants released from various industries cause water pollution. This contaminated water causes many diseases which affect all around the world. This study investigated the use of metal oxide nanoparticles for wastewater treatment. This is the first study that reports the biosynthesis of ZnO nanoparticles using leaf extract of thumba. The structural and morphological study of prepared nanoparticles were investigated using UV–Vis spectroscopy (UV–Vis), Fourier transforms infrared spectroscopy (FT-IR), Energy dispersive X-ray spectroscopy (EDAX), and Transmission electron microscopy (TEM). ZnO nanoparticles prepared from thumba leaf extract can be used as an effective antimicrobial and antibacterial agent. ZnO nanoparticles exhibited higher antibacterial activity against Gram-negative bacteria, especially Escherichia coli. The study also revealed the use of ZnO nanoparticles in the textile industry which prevents the growth of E. coli bacteria in the textile fabrics [23].

Mahendiran et al., (2017) study conducted on Biosynthesis of ZnO nanoparticles using plant extracts of Aloe vera and hibiscus sabdariffa. This study also investigated the photochemical, antibacterial, and antiproliferative activities of the zinc oxide nanoparticles. In this study zinc oxide (ZnO) nanoparticles were synthesized using extract of Aloe vera leaf and hibiscus sabdariffa leaf. Here the chemical method is also used for comparison purposes. The chemical method of this study uses zinc nitrate and sodium hydroxide solutions, and the biological method uses leaf extract of Aloe vera, H. sabdariffa, and zinc nitrate. The obtained nanoparticle was characterized using FT-IR (Fourier Transform Infrared Spectroscopy), UV-Vis (Ultraviolet-Visible spectroscopy), XRD (X-ray Diffraction), SEM (Scanning Electron Microscopy), and EDX techniques. This study concludes that UV-Vis spectra revealed characteristic absorption peaks at 370nm. XRD and SEM images revealed the hexagonal structure of ZnO nanoparticles with an average size ranging between 9 and 18nm. EDX assessment indicates the purity of obtained nanoparticles without many impurity peaks. This study also suggests that biosynthesized ZnO nanoparticles are more effective in bactericidal activity compared to chemically synthesized nanoparticles. This work on the biosynthesis of ZnO nanoparticles promises an eco-friendly approach with almost zero contamination in the environment because they are obtained from plant extracts [24].

The biological synthesis of ZnO nanoparticles using medicinal plants has received profound interest because of their potential applications in the biomedical field. John et al., (2016) reported the Biosynthesis of ZnO nanoparticles using Ocimumtenuiflorum leaf extract. The study suggested that nanomaterials produced from plant extracts are more stable and the synthesis rate is larger as compared to those produced via other conventional methods. Quantitative and morphological properties of obtained nanoparticles were studied using UV-Vis spectroscopy, Fourier Transform Infrared spectroscopy (FT-IR), Field Emission Scanning Electron Microscope (FE-SEM), Energy-Dispersive X-ray spectroscopy (EDX), atomic force microscopy, zeta potential, X-ray Diffraction (XRD), and photoluminescence intensity (PL). The absorption peak was found to be at 380 nm which reveals the antioxidant property of ZnO nanoparticles. Where zeta potential analysis showed the effect of Ocimumteniflorum leaf extract on the ZnO nanoparticle surface chemistry. Zeta potential value decreases with decreasing extract concentration, affecting the surface chemistry and stability of ZnO nanoparticles [25].

Geetha et al. (2016) research explained a novel approach for the production of antibacterial zinc oxide nanoparticles through the utilization of a biopolymer known as neem gum. The core objective of this research was to explore a green and sustainable method for producing nanoparticles with antimicrobial properties. The study capitalized on neem gum's inherent characteristics to mediate the formation of these nanoparticles, aligning with environmentally friendly practices. This biopolymer played a crucial role in both the reduction of zinc ions and the subsequent transformation into zinc oxide nanoparticles. By using neem gum as a reducing agent, the study presented a biologically friendly pathway to nanoparticle fabrication, reducing the reliance on conventional chemical agents. To thoroughly assess the properties of the prepared nanoparticles FTIR, SEM, and XRD were used. The study's outcomes confirmed the presence of zinc oxide nanoparticles exhibiting hexagonal wurtzite structures. This structural configuration is a characteristic of zinc oxide and is a significant indicator of the material's crystalline nature. The size range of the nanoparticles was determined between 30-60 nm, offering insight into their dimensions [26].

Bhuyan et al., (2015) analyzed the biosynthesis of ZnO nanoparticles from azadirachtaindicafor antibacterial and photocatalytic applications. Biosynthesized nanoparticles were examined using TEM (Transmission Electron Microscopy), EDX (Energy Dispersive X-ray analysis), UV-Vis (Ultraviolet-Visible spectroscopy), XRD (X-ray diffraction), and FTIR (Fourier Transform Infrared Spectroscopy) techniques. The study concludes that ZnO nanoparticles synthesized using neem leaf extracts act as an effective reduction. The ZnO nanoparticles were spherical with a size range of 9.6-25.5nm. The ZnO nanoparticles produced have shown high antibacterial and photocatalytic activity [27].

Noorjahan et al., (2015) study illustrated green synthesis and characterization of zinc oxide nanoparticles from Neem (Azadirachtaindica). In this study, zinc oxide nanoparticles are synthesized from aqueous Neem leaf extract. Synthesized nanoparticles were characterized using XRD FTIR, SEM, TEM, and UV-Vis techniques. FT-IR analysis indicates the reduction and capping agents present in the nanoparticles. SEM study revealed the formation of nanoflakes and spindle-shaped nanoparticles with a size of 50μm [28].

Yuvakkumar et al., (2014) deal with the non-toxic green synthesis of zinc oxide nanocrystals using Rambutan (nepheliumlappaceum L.) peel extract and explain its antibacterial applications. This is the first report that used Rambutan peel for the synthesis of zinc oxide nanocrystals which act as a natural ligation agent. The formation of ZnO nanocrystals was confirmed using standard characterization studies. This study proposed a possible mechanism for the synthesis of ZnO nanocrystals with Rambutan peel wastes. Produced nanocrystals were coated with cotton fabrics and analyzed their antibacterial activity towards different bacterial pathogens such as E. coli, and S. aureus. The study concludes that SEM and EDX images confirmed the absorption of cotton-fabricatedZnO nanocrystals. Due to the increasing ZnO nanocrystal absorption, ZnO nanocrystal-coated cotton fabrics exhibited stronger antibacterial activity [29].

Gnanasangeetha et al., (2013) reported the one-pot synthesis of zinc oxide nanoparticles via chemical and green methods. The green method used aqueous leaf extract of corriandrum sativum and the chemical method used zinc acetate and sodium hydroxide solutions. The synthesized nanoparticles are characterized using XRD, SEM, FT-IR, and EDAX techniques. The study concluded that green methods are a better choice for nanomaterial fabrication compared to chemical methods due to eco-friendliness. FT-IR study reveals the presence of alcohol, aldehyde, and amines in zinc oxide nanoparticles. XRD reveals the average size was 66nm in the green method and 81nm in the chemical method [30].

The study conducted by Ravindra et al. (2011) focused on the utilization of a biological method to synthesize and characterize zinc oxide nanoparticles. The researchers used calotropisprocera leaf extract at ambient temperature to create these nanoparticles. To gain insights into the physical attributes of the produced nanoparticles, a variety of spectroscopic techniques are used. The investigation unveiled that the zinc oxide nanoparticles exhibited a spherical and granular morphology, falling within the size range of 5-40 nm. To understand the emission properties of these nanoparticles, the researchers conducted photoluminescence (PL) studies. These investigations shed light on the emission characteristics of the nanoparticles. One notable outcome of this study was the demonstration of a simple, environmentally friendly, and cost-effective method for generating zinc oxide nanoparticles. This advancement holds significant promise for applications in both the biomedical sector and the photonics field [31].

4. Discussion

The studies mentioned above have made significant strides in the field of green synthesis of zinc oxide nanoparticles, they also face certain challenges that are inherent to this area of research. The varying composition of plant extract from different sources can lead to inconsistencies in nanoparticle properties. Additionally, controlling the adsorption and photocatalytic activity of the synthesized nanoparticles on a practical scale can be challenging due to factors like reproducibility and scalability. In green synthesis methods challenges lie in achieving precise control over the size and morphology of nanoparticles. Variability in plant extract composition and synthesis conditions can lead to variations in particle size, which can impact the desired applications in various fields. In the study conducted by Priyadharsini et al, a key challenge is optimizing the antibacterial properties of the synthesized nanoparticles. While the study demonstrates enhanced antibacterial activity through manganese doping, achieving consistent and reliable results across different strains and concentrations can be indicated. The potential cytotoxicity of these nanoparticles in real-world medical applications needs to be thoroughly explored. The research explained by Ramesh et al, a major challenge is in achieving reproducibility in latent fingermark development using synthesized nanoparticles. Environmental conditions, surface variations, and specific interactions between nanoparticles and fingermark components can influence the efficiency of this application. In the study by Saurabh Sharma et al, a significant challenge lies in the correlation between nanoparticle size and shape with specific antimicrobial and photocatalytic activities. Biological systems are inherently complex, and the interplay of these nanoparticles with microorganisms or pollutants can be influenced by multiple factors beyond size and shape, such as surface charge and interaction dynamics.

The studies presented above have several research gaps that present opportunities for future exploration and advancement. There is a need for standardizing protocols in green synthesis methods using plant extracts. Variability in plant species, extraction techniques, and synthesis conditions can lead to inconsistencies in nanoparticle properties. Establishing standardizing protocols will enhance reproducibility and comparability across different studies. A deeper understanding of the mechanisms responsible for nanoparticle formation using plant extracts is essential. Identifying the specific compounds responsible for reduction and stabilization, and understanding how they interact with metal ions, will provide insights into the synthesis process and aid in optimizing nanoparticle properties. Different factors, such as plant growth conditions, geographic location, and seasonal variations, can influence the composition of plant extracts. Future research should investigate how these variations impact nanoparticle synthesis and how to mitigate their effects for consistent nanoparticle production. Green synthesis methods are environmentally friendly but translating them to large-scale production remains a challenge. Future studies should focus on developing scalable processes that maintain the eco-friendly aspects while ensuring cost-effectiveness. While the green synthesis approach suggests reduced toxicity, thorough toxicity and biocompatibility assessments are essential for potential biomedical and pharmaceutical applications. Investigating the long-term effects and interactions of these nanoparticles with loving systems will be critical. Advanced characterization techniques are needed to precisely analyze the synthesized nanoparticles and understand their attributes. Developing techniques that can differentiate between nanoparticles with differences in size, shape, and composition will be valuable for accurate characterization.

In conclusion, the field of green synthesis of nanoparticles using plant extracts holds immense promise, but several research gaps need to be addressed to fully unlock its potential. Future research should focus on standardization, mechanistic understanding, scalability, advanced characterization, applications, and toxicity assessments. Real-world applications, comparative studies, and interdisciplinary collaboration. Addressing these gaps will contribute to advancing and practically implementing eco-friendly nanoparticle synthesis methods.

5. Advantages of biosynthesis

Nanoparticles synthesized using green methods outperform those generated through physical and chemical methods across multiple dimensions. Green synthesis eliminates the need for costly chemicals, reduces energy consumption, and results in non-toxic byproducts that pose minimal harm to the environment [32]. When aiming to produce biocompatible and stable nanoparticles, green technology stands as the preferred approach. A diverse array of phytochemicals including terpenoids, flavonoids, ketones, aldehydes, amides, and carboxylic acids play a vital role in enhancing the bioactivity of these nanoparticles [33]. Notably, plant leaves are readily accessible, easy to manipulate, safe, and even act as both capping and stabilizing agents themselves. In contrast to nanoparticles synthesized using microorganisms, which necessitate prolonged incubation periods for the reduction of metal ions into metal oxide nanoparticles, leaf extracts encompass a multitude of phytochemicals capable of efficiently converting metal ions into metal oxide nanoparticles [34]. Consequently, leaf extract serves as an exceptional resource for synthesizing metal oxide nanoparticles due to the convenience of extracting the abundant phytochemicals [35].

6. Conclusion

The objective of this review was to provide comprehensive insights into the production and analysis of ZnO nanoparticles through abundant plant extracts and explore their potential in biomedical contexts. Numerous research studies have showcased the feasibility of generating ZnO nanoparticles through environmentally friendly methods involving diverse medicinal plant extracts. Furthermore, the source of these extracts, the plant parts utilized, and a range of applications have been documented in the referenced literature. Emphasizing the medical applications of ZnO nanoparticles produced from various plants all over the world, this review spotlights their remarkable potential in addressing conditions such as cancer, diabetes, microbial infections, and inflammation. Additionally, these nanoparticles have demonstrated significant antibacterial efficiency, rendering them suitable for external applications like wound healing and the coating of medical devices. Within this review, we focus on thespecifics of the biogenic synthesis, characterization, and diverse biomedical uses of ZnO nanoparticles, specifically bio-imaging, bio-sensing, and the detection of cancer cells.

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